TELESCOPE MAKING 16

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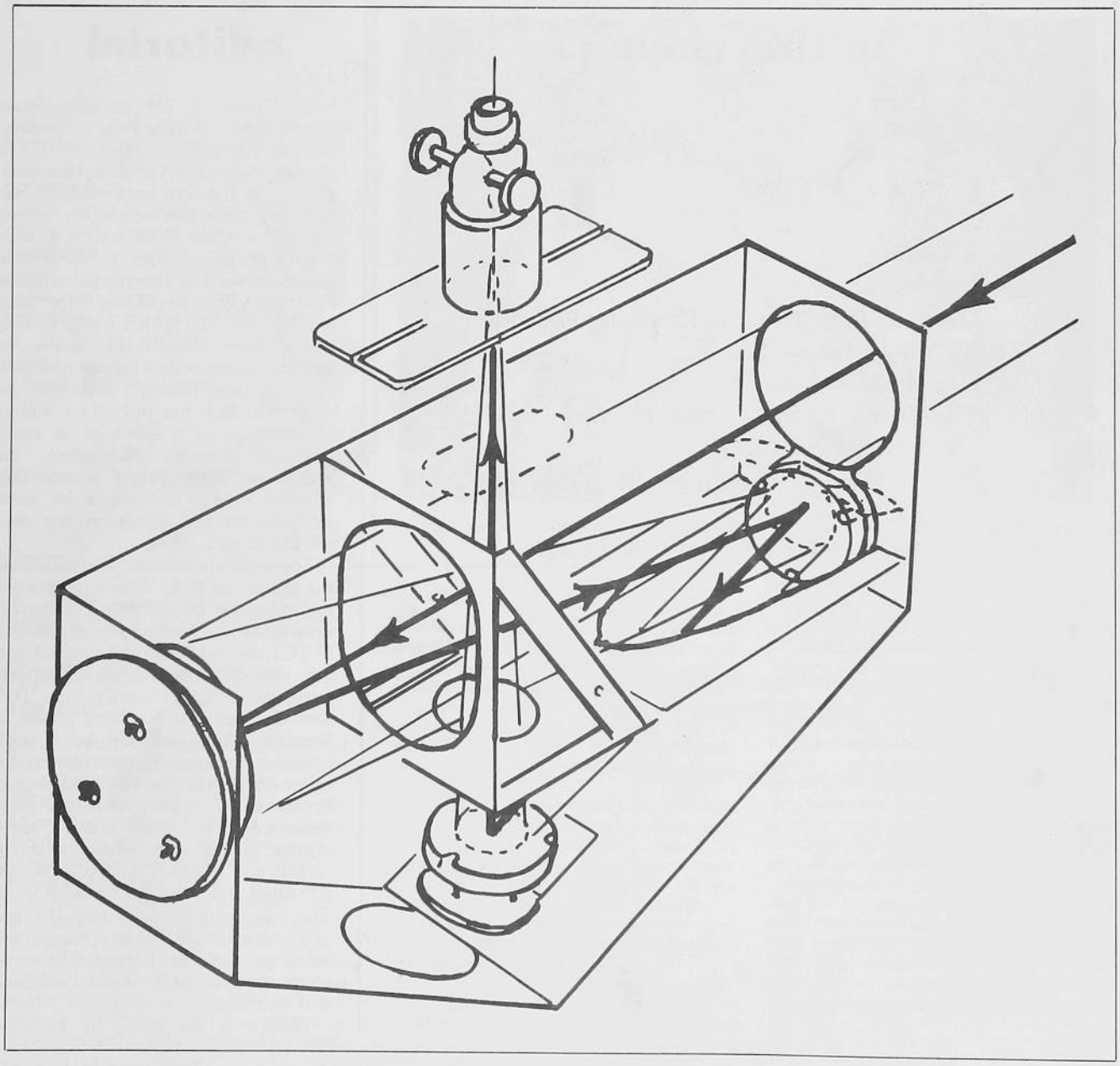
The magazine *for*, *by*, and *about* telescope makers!

Summer 1982



TELESCOPE MAKING

The magazine *for, by* and *about* telescope makers!

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Associate Editor: Robert E. Cox

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Editorial

This issue of TM contains fewer articles than any issue I can remember. But, as you will see, they are HUGE articles. Many of us, I am sure, have been waiting for the final installment of Bob Kestner's three-part article on making big, thin mirrors. After editing it, then reading the galleys, then reviewing them with Bob (two hours long distance to San Francisco), then re-reading it for typos and the like, I've gotten pretty familiar with it. I have to admit that I'd be a lot less afraid of undertaking a big one now than I've ever been before. I hope that the effort that Bob has put into it will be rewarded — with some of us really following through. Meanwhile, the section on "Star Testing" is incredibly valuable — I've become a lot more sensitive to the optics in my own telescopes as a result.

The wealth of information on TCTs in the articles by A. L. Woods tempts one to undertake one of those extremely crisp systems. I looked through Woods' 6″ TCT two years ago at AstroFest, and the images those things deliver are remarkable. Art Leonard's Yolo TCT was the best for resolving power at Riverside. And, well, just being really honest with yourself, how dark is the space between the components of Epsilon Lyrae in your telescope? Most telescopes I've used show "hairy" images, so that even when the pair is cleanly split, there is quite a bit of light diffracted and scattered between them. The only instrument I've seen that can compete with a TCT is an apochromatic refractor such as Roland Christen's, shown last year at Riverside, Stellafane, and AstroFest.

There's a lot going in favor of

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unobstructed apertures, as van Venrooij's paper in this same issue points out. It bears close reading and consideration.

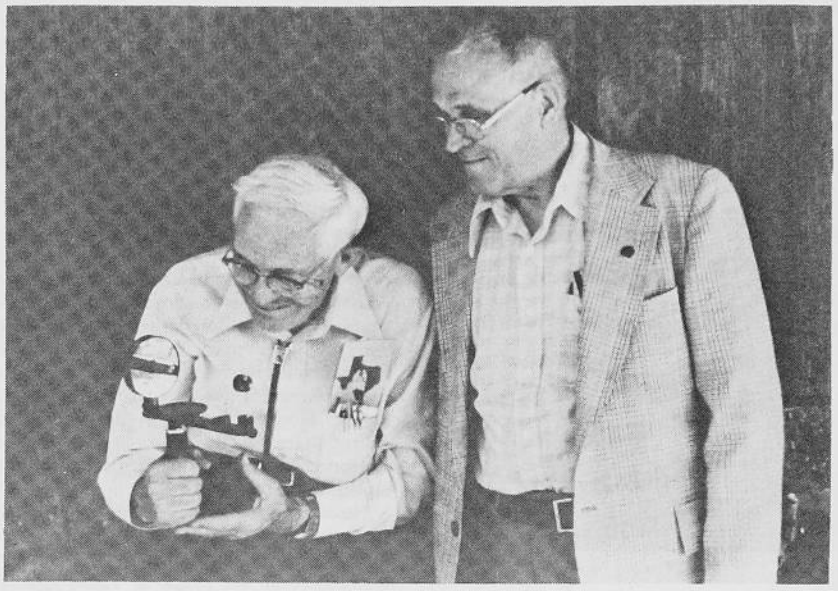
This issue is going out about three weeks late due to time I lost with pneumonia in May. Hopefully, the printer will be extra-fast and we can make up some of the lost time. Meantime, by the time TM#17 is ready to go, I'm betting we'll be up to schedule again.

See you at Stellafane!

Sincerely,

Richard Berry

Richard Berry
Editor



Bob Cox reports on the Texas Star Party — coming in TM#17. Photo shows Bob and Clyde Tombaugh.

Letters

Horrible Subscription Tangle

Dear Mr. Berry / Thank you for your letter dated March 15, 1982 and for the back issues of TELESCOPE MAKING which were included. Just to cheer you up, I would like to tell you that I received TM#10, 11, 12, 13, and shortly later #14. In turn I sent another airmailed postcard explaining that the problem was actually solved.

Anyway, the copies you enclosed in your letter were #11 to 14, which I had also received as regular subscription. To that end, my subscription period is commencing with #10 and should expire with #29 (whereas the mailing label suggests #28, which fact I have already highlighted to the circulation department with another airmailed postcard).

When I received the first lot of TM I found it was such a good magazine that I sent a second order to your circulation department, asking them to send back issues #1 through #9. I enclosed $27 with that letter. The $27 was meant to cover 9 x $2.50 + mailing + copy of ASTRONOMY, which you had already included with your free delivery. Great confusion, isn't it?

When I thought about what I should do with the duplicate lot of TM that I received from you, I had the idea of giving them to a colleague, H. Mohr, who is also a keen telescope enthusiast, so I believe he will end up as a new subscriber to TM, hopefully.

I am sure you will be able to clear this mess up and let me know about the arrangements you have made on my behalf.

Karl-Hermann Klein
Regengasse 37
5014 Kerpen
Germany

— Thanks for your good humor in helping us get your problem resolved. The reason it takes so long to start a subscription to TM is that our circulation department "batches" orders for TM only once per month, and the sub starts with the next issue published. If the timing works out poorly and we receive your check just after an issue goes out, it won't be processed for four weeks, we won't mail your next issue for eleven weeks, and it will spend another three weeks in the mail before reaching you. A foreign subscription takes eight to ten weeks in transit.

We also wish to apologize for the confusion that the last issue number on the mailing labels has created. Our computer house (who shall remain un-named) can't seem to get their program together to print it right. Although you are properly credited in our records for the issues you have paid for, the

Letters

label is incorrect. All the TM#14 labels had the expire one issue too soon. When they attempted to rectify the problem on TM#15's labels, they went the wrong way, and the labels all show expiration two issues too soon.

I've been promised that TM#16 will be correct.

— RLB

Claimed Credit

Dear Mr. Berry / I am the one who sent the pictures in TM#15, page 4. I never take the mirror out of the tube, since I have dustproof covers for each end and a plug for the eyepiece holder hole. I can carry the telescope into the garage myself because it weighs only 50 pounds. By the way, it's not a 17", but a 12.5" made with a 1" thick blank that I bought at a garage sale for $1.00 — so you can see that I just had to build this one!

George Neal
Box 258-A, Rt. 2
Lindstrom, MN 55045

MASCON '81

While the North American coasts are well served by Stellafane and Riverside, the center of the continent is not. We were pleased to hear of a new astronomical gathering and telescope competition that began this year near Winnipeg, Manitoba. Here are a few photographs of the telescopes in MASCON '81, the Manitoba Astronomical Convention that was held in Riding Mountain National Park.

Robert Buss, of Dickinson, North Dakota, won an award for his 5-inch refractor. The wooden mounting has good stability because of its mass, but it is still compact. Buss was assisted by Dave Heuther, also of Dickinson. Stan Runge of Winnipeg showed his 6-inch f/5 reflector. The low "sitting dog" inverted fork mounting is ideal for children. At nearby Glenlea Observatory, the Winnipeg Centre of the RASC offers its members permanent mounting sites on a concrete pad for a variety of telescopes.

David H. Levy
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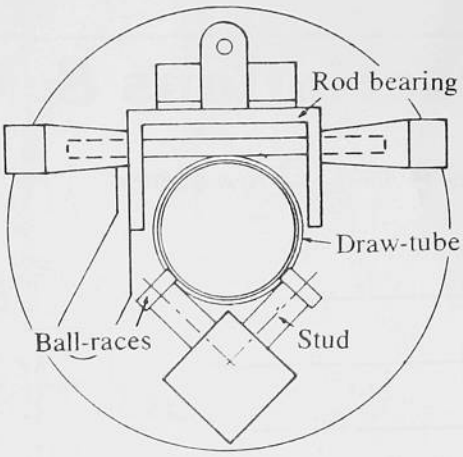
Tucson, AZ 85706



Crayford Drawing

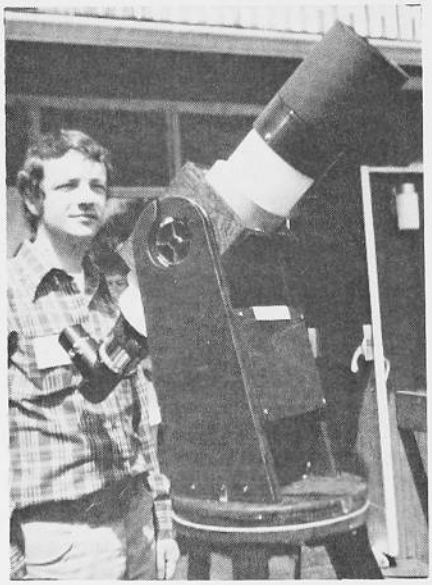
Dear Mr. Berry / As the results of my article "The Crayford" in TM#11, I have had several letters from as far apart as Belo Horizonte (Brazil), Los Angeles, and places between asking for more details. Unfortunately you did not publish the diagram I sent explaining what they want to know. I am sending another copy in case you think it worthwhile to include it in a future number. One of my correspondents, James Murta of Glendale, CA, was in England during the last war (in the U.S. Air Force) and was very interested, and visited, the Royal Observatory Greenwich, London. He urged me, very strongly, to visit it if I had not already done so. I was able to inform him I was born within half a mile of it, wheeled around it in my pram by my mother during the summer of 1903. I have many friends there: Nigel Henbest and Heather Couper are lecturers at the Planetarium (which I visited last week); Derek Howse, President of the British Astronomical Association, is "Keeper" of Astronomy and Navigation, as the head is styled; and others.

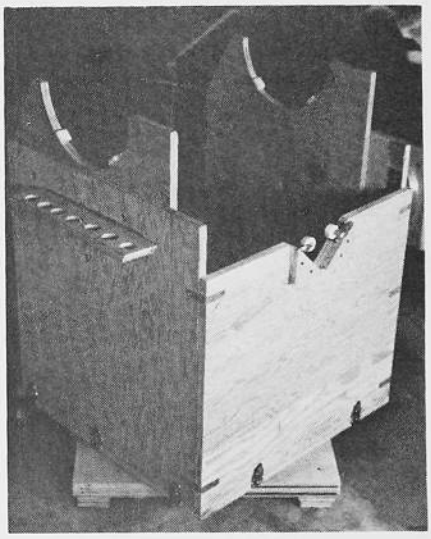
Now a mystery. In TM#15, page 5, our names with one or two others, are linked in a foreign language panel. Why? It seems to be a translation of the index of TM#8 where I described my observatory, and you, Dobsonian Friction Control. I am most puzzled. Can I have the explanation please. What language is it? I think it is Russian because of the "CCCP." Am I correct?

Many congratulations on TM. It seems to be getting popular over here.

Reg Spry
60 Windsor Rd.
Selsey, Sussex P020 0AU
England

— Sorry about the missing diagram. Its absence was an oversight. Incidentally, Reg Spry had published a book on building simple telescopes several years ago — which I came across by accident in the Milwaukee Public Library. Unfortunately, I don't remember the title, but you can always look under the author's name in the index. Now for the mystery, Reg, you are right that the language is Russian. TELESCOPE MAKING is reviewed by the USSR Academy of Sciences, and the abstracts published in their Abstracts Journal. *Their initial letter to us appeared in TM#8, page 37. They send us mysterious little clippings from time to time, and I stick them in "Letters" because we might as well all know what the Russians are saying about us. The first of the little reviews was in TM#11. They seem to be about a year and a half behind. Incidentally, we are also reviewed in the annual* Index To How To Do It Information *published by Norman Lathrop Enterprises for professional librarians. TM accounts for the bulk of entries under "Telescopes."*





Disassembling the Dobsonian Base

Dear Mr. Berry / I enclose some photos of my recently completed 16" Dobsonian mounted scope. You can see we made some modifications in the basic mounting when some friends and I put it together. The base comes apart into two large sections and the walls and front fold together so that I end up with two flat pieces that are much easier to store and put into a car for transportation.

Although the unit is quite stable, it isn't quite as steady as if the whole base were built as one piece. I think the portability makes up for it, however. There's also a handy folding

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Contrast Rendition and Resolving Power in Telescopes Used Visually

Most amateurs test their telescope optics on double stars. But the ability to resolve close doubles does not always measure the capability to resolve details on lunar and planetary surfaces. Images of extended objects are much more complicated than images of point sources because we have to deal with a multitude of details of different size, shape, color, brightness and contrast.

You might consider a surface detail as being composed of an indefinite number of bright and less bright point sources. Every one of these hypothetical point sources will form its own diffraction pattern in the focal plane, the final image being the composition of the overlapping diffraction patterns.

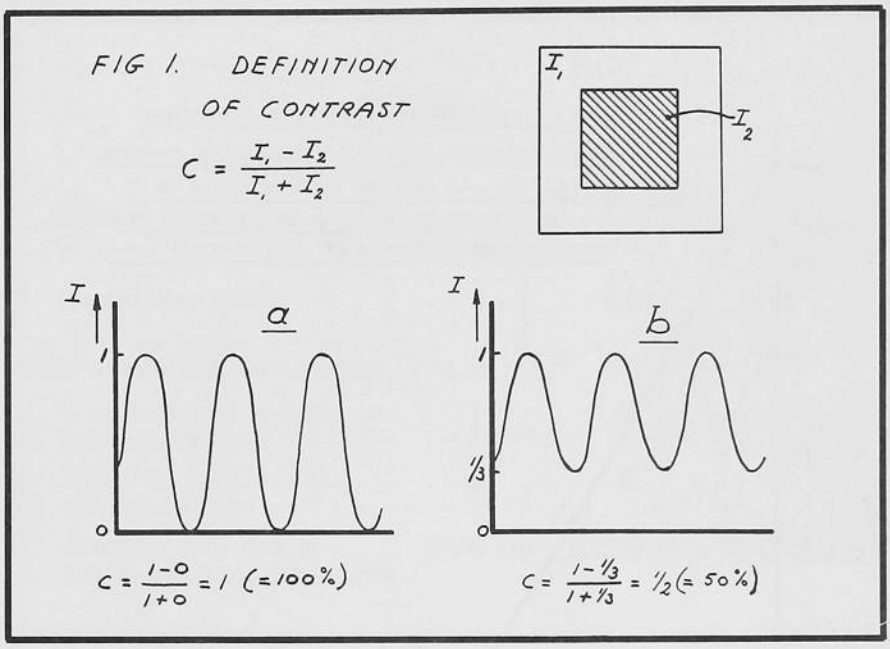
Large uniformly illuminated surfaces will be uniformly illuminated in the image as well. No unsharpness will be visible here. Noticeable diffraction effects, resulting in unsharpness, will be only present at the borders of surfaces with different brightness. Since the image of an extended detail can be very complicated, it is difficult to find a representative and reproducible method to define the resolution of an optical system for these kind of images.

However, in 1946, P.M. Duffieux developed the concept of contrast transfer in an optical system. This approach yields considerable insight into what happens in the image forming process when extended details are observed.

For detail to be visible, even when the aperture, magnification and resolving power of the telescope are sufficient, there must also be adequate image contrast. If the image contrast is below the eye's visibility threshold, then the detail will be invisible. The image contrast depends not only on the inherent contrast in the object (i.e., the contrast of faint markings on Saturn), but also on how much contrast the optical system transfers into the image plane. The concept of contrast transfer is the key for understanding, for example, why a planetary detail is visible in one telescope but not in another of the same aperture.

Resolving power and contrast transfer are both quality criteria for every telescope. Today it is possible to measure the contrast transfer of an optical system with special equipment, and the relation between image contrast and resolution can be determined for every point on the image plane.

In this article we will give a popular general treatment of contrast transfer for optical telescopes. We will focus our attention on a comparison between an obstructed and unobstructed telescope and analyze comprehensively the optical performance for these systems for visual use.



Contrast Transfer for a Perfect Optical System

An optical system can be characterized as "perfect" when, neglecting diffraction, it produces a point image in the focal plane if the source is a point. Moreover, no internal reflections or stray light should reach the focal plane, and no obstruction such as a secondary mirror or spider should be present. When a telescope meets these criteria, then the Airy diffraction pattern will have the ideal intensity distribution. Before discussing the contrast transfer of this perfect system, let's define contrast and contrast transfer. The contrast between two adjacent surfaces with the illumination intensities I_1 and I_2 is defined as:

$$C = I_1 - I_2 / I_1 + I_2 \text{ , when } I_1 > I_2.$$

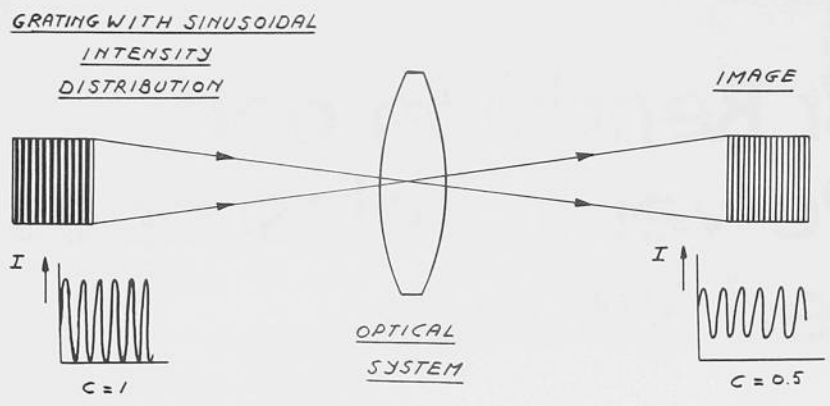
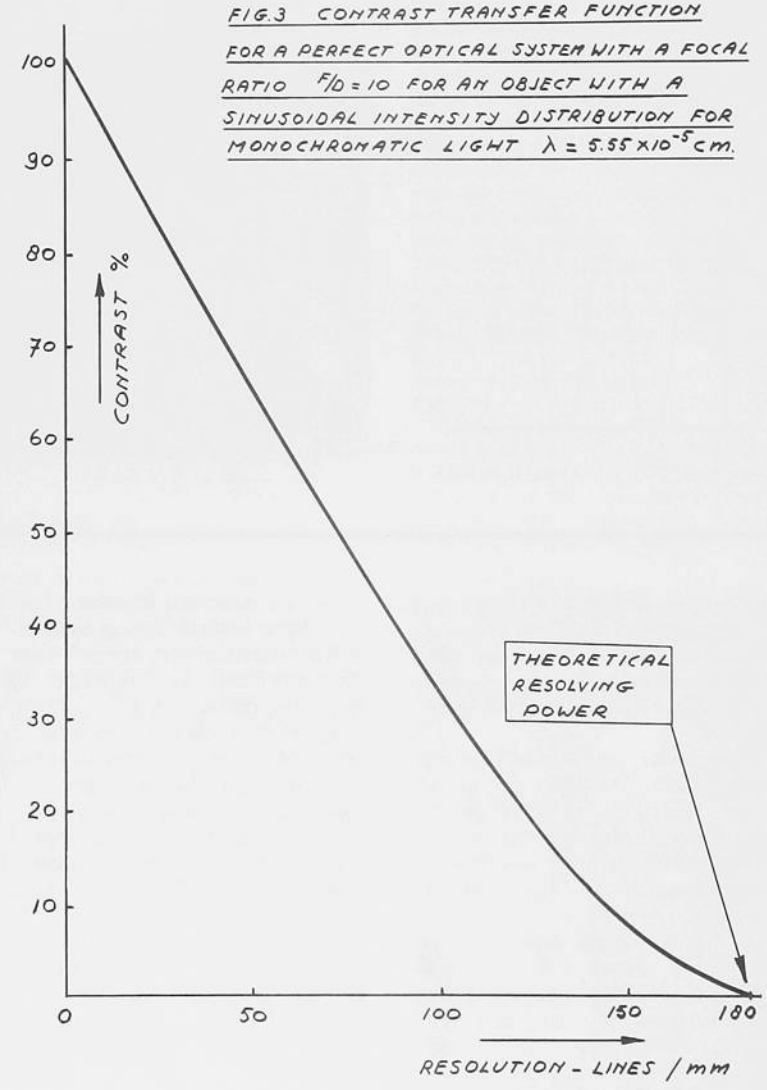


FIG. 2. CONTRAST TRANSFER BY AN OPTICAL SYSTEM

FIG.3 CONTRAST TRANSFER FUNCTION FOR A PERFECT OPTICAL SYSTEM WITH A FOCAL RATIO F/D = 10 FOR AN OBJECT WITH A SINUSOIDAL INTENSITY DISTRIBUTION FOR MONOCHROMATIC LIGHT $\lambda = 5.55 \times 10^{-5}$ cm.



Using this definition, all values of contrast can be expressed in figures between 0 and 1 (or 0% and 100%). Suppose we examine two sinusoidal intensity distributions in a grating of parallel lines. If the intensity varies between 0 and 1 units, the contrast between the highest and lowest intensity is:

$$C = \frac{1 - 0}{1 + 0} = 1 \ (= 100\%)$$

But if the intensity varies from 0.33 and 1, the contrast is then:

$$C = \frac{1 - .33}{1 + .33} = 0.5 \ (= 50\%)$$

In principle, measurement of the contrast transfer is carried out by placing a grating with a sinusoidal intensity distribution as an object in front of the optical system. The number of lines per inch in the grating is varied, and the contrast in the image of the grating is measured.

The ratio between image contrast and object contrast is called the contrast transfer coefficient. The contrast transfer coefficient would be:

$$CTF = \frac{c \text{ (image)}}{c \text{ (object)}} = \frac{0.5}{1} = 0.5 = 50\%$$

A graph of the relation between the contrast transfer coefficient and the number of lines in the image is variously called the contrast transfer function, or CTF, or the modulation transfer function (MTF) or optical transfer function (OTF). Duffieux found that the contrast transfer function for a perfect system is a smoothly decreasing monotonic curve.

As the number of lines increases, the optical system renders them with lower and lower contrast because every point in the object is represented by a diffraction pattern in the image. This diffraction pattern scatters light around every image point so that the dark places in the image are illuminated by scattered light. This effect becomes more important as the distance between elements in the image dwindles to approach the size of the diffraction pattern. Eventually, at some value, the image contrast is reduced to zero. The image of the grating will then be uniformly bright and without any structure. This is the highest resolving power the system can attain.

Contrast Transfer for Imperfect Optical Systems

CTF curves are useful because we can compare the performance of imperfect optical systems with the ideal curve. Since the CTF of real systems is the accumulation of both diffraction effects and various aberrations, we gain information about the magnitude of image aberrations.

Imperfect systems usually have curves

that lie below the ideal CTF. This means that for the same resolution, the image contrast of the imperfect system is lower than for the perfect system. The reason for that is that image aberrations generally cause additional scattered light. Spherical aberration, coma, astigmatism, and chromatic aberration are important, but the CTF curves also show unsmoothness in the optical surfaces and the influence of the spider and secondary mirror. These produce a diffraction pattern with diffraction rings that are brightened at the cost of the Airy disk. Even between the rings, light will be visible. The influence of aberrations on the CTF is shown in Fig. 5. Another such graph was given in the article about the Bird Jones corrector (TM #3, page 16).

Other contrast diminishing effects in an optical system are internal reflections and stray-light. Fig. 6 shows their influence on the CTF — the contrast is reduced by the same percentage for all resolution values.

The Effect of a Central Obstruction

One subject of ongoing, and seemingly never-ending, discussion among amateurs, and therefore probably the most interesting for the reader, concerns the reduction in contrast caused by the central obstruction in a mirror telescope. This happens in Newtonians, Cassegrains, and catadioptric telescopes.

First, how are the Airy disk and diffraction pattern affected? This is shown in Fig. 7 — the diameter of the Airy disk for an obstructed system is actually slightly reduced with respect to an unobstructed system, but the rings are brightened at the expense of the central intensity of the Airy disk.

Table 1 gives the influence of the

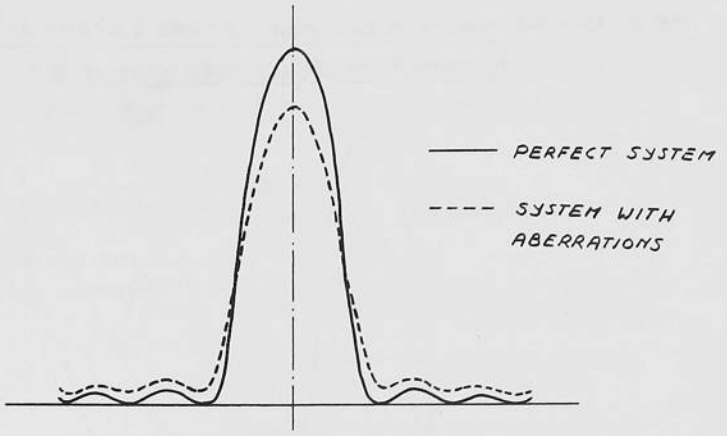


FIG 4. DIFFRACTION PATTERNS FOR OPTICAL SYSTEMS WITH AND WITHOUT ABERRATIONS

Table 1

Type of Telescope	Refractor Schiefspiegler	Newtonian	Cassegrainian
Obstruction Ratio	**0**	**0.25**	**0.50**
% of total light in Airy-disk	84	73	48
% of total light in first diffraction ring	7	18	36
% of total light in other diffraction rings	9	9	16
diameter Airy-disk in arc-seconds for green light	28/C cm	26.2/D cm	23/D cm

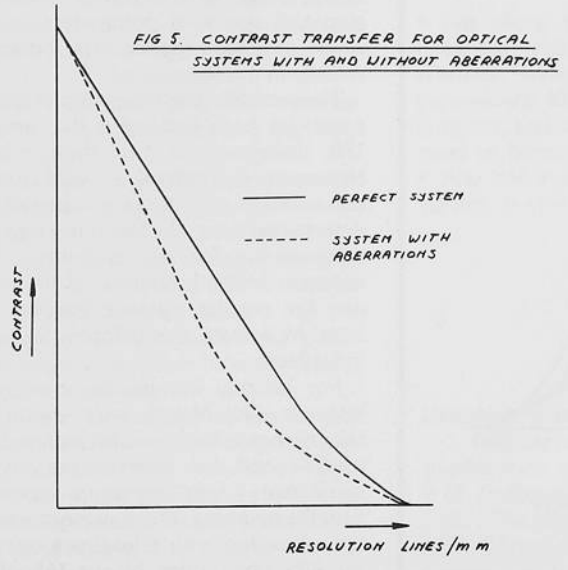


FIG 5. CONTRAST TRANSFER FOR OPTICAL SYSTEMS WITH AND WITHOUT ABERRATIONS

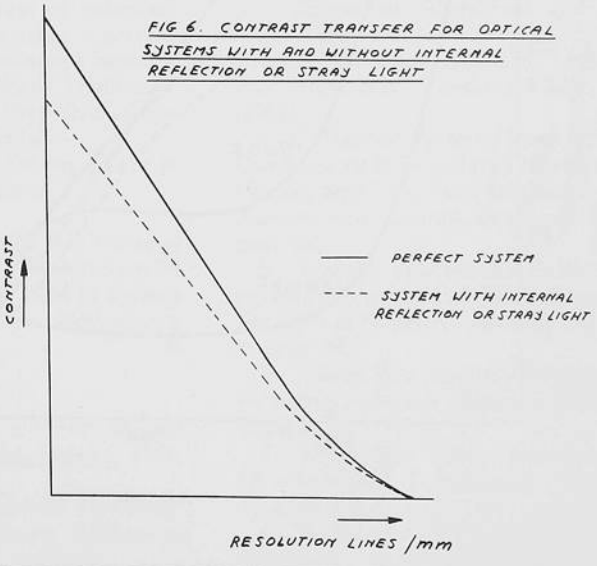


FIG 6. CONTRAST TRANSFER FOR OPTICAL SYSTEMS WITH AND WITHOUT INTERNAL REFLECTION OR STRAY LIGHT

FIG 7 DIFFRACTION PATTERNS FOR OPTICAL SYSTEMS WITH AND WITHOUT CENTRAL OBSTRUCTION

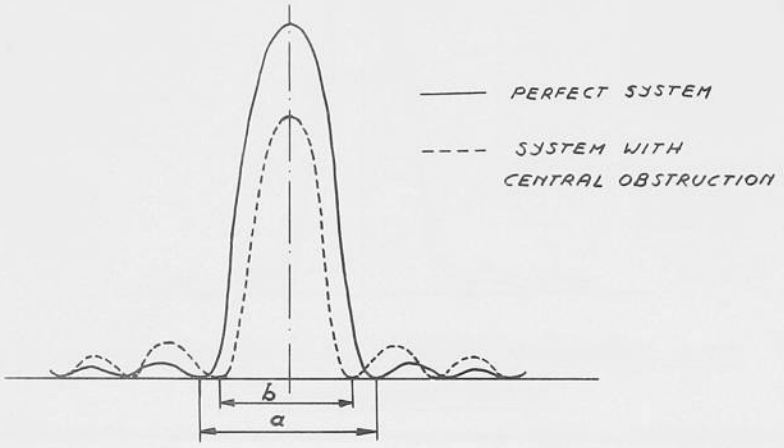
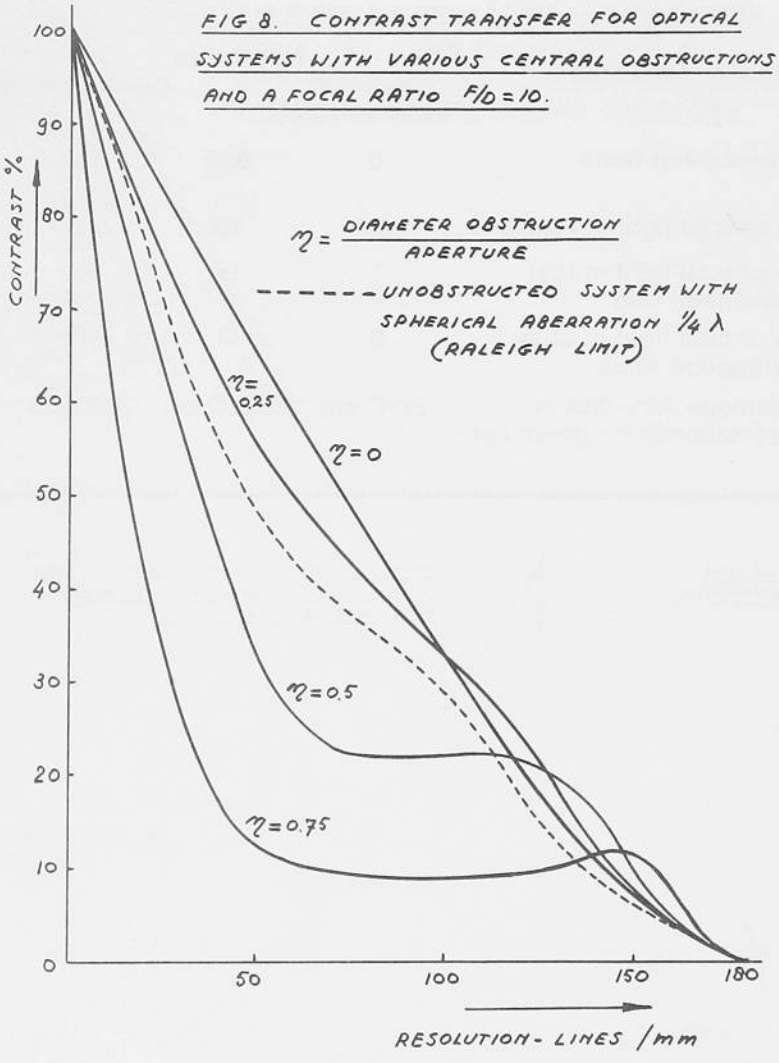


FIG 8. CONTRAST TRANSFER FOR OPTICAL SYSTEMS WITH VARIOUS CENTRAL OBSTRUCTIONS AND A FOCAL RATIO F/D = 10.



obstruction ratio, eta, on the Airy-pattern for some typical cases, and Fig. 8 shows CTF curves for systems with eta, the obstruction ratio, equal to zero, 25%, 50%, and 75%.

The curves clearly show the loss of contrast in obstructed systems as a result of the additional scattering of light in the Airy-pattern. Surprisingly, for higher resolutions, the contrast appears to be somewhat enhanced for obstructed systems. The reason for this is that the Airy disk diameter is smaller when a large central obstruction is introduced.

For comparison, look at the CTF for an unobstructed system with 1/4-wave of spherical aberration, corresponding with the Raleigh limit on wavefront errors. From Fig. 8, we can draw the following conclusions:

- for a 25% obstruction, the loss of contrast is not severe, amounting to a maximum of 15% with respect to the unobstructed system at 60 lines/mm.
- the CTF curve for a system having 1/4-wave length spherical aberration corresponds roughly with an obstruction of 30%; that is, a 30% obstruction is roughly as bad as a 1/4-wave error in the optical system.
- an obstruction of 50% causes considerable loss of contrast, approximately 55% at 70 lines/mm.
- the contrast for a system having a 75% obstruction, hardly used in practice, would be very poor.

A Comparison of Obstructed and Unobstructed Telescopes for Visual Use

Now, by means of the CTF, we will compare an unobstructed system and a system with a 40% obstruction, typical of a Cassegrainian. Both systems have the same aperture and focal ratio f/10. Although Fig. 9 looks rather complicated at first glance, we'll go through it step by step and see what parameters matter when extended details are observed visually in a telescope.

Theoretically the maximum resolving power for both systems is the same — 180 lines/mm in the focal plane. However, the effective resolution in combination with the eye can only be determined when the minimum required contrast for the eye is known. This depends on the brightness of the image and the angular distance between the lines. Moreover, it is different for every individual.

For brightly illuminated objects, for instance the Moon, we'll assume a minimum required contrast for fine detail of 5%, and for coarser patterns, a somewhat lower minimum contrast. Strictly speaking, these are not exactly the same for both telescopes because the 40% obstruction blocks 16% of the

light. We have neglected this effect here.

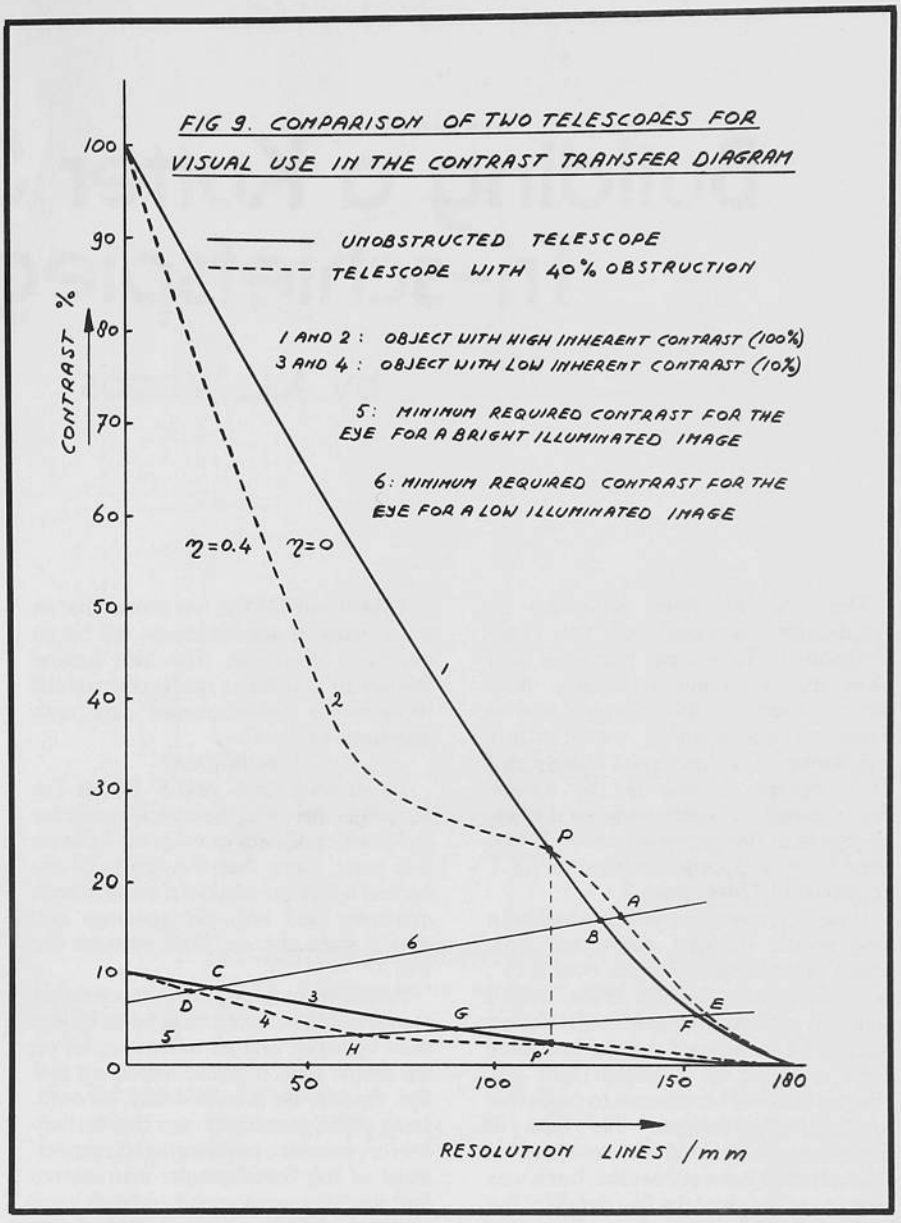
In order to distinguish details for dimly illuminated objects, the eye needs higher image contrast as shown in curve 6.

The resolving power for a combination of a telescope and the eye is determined by the intersection of the CTF curves and minimum required contrast curve of the eye. Here, however, another very important factor enters, the inherent object contrast. It must be understood that curves 1 and 2 show contrast transfer from an object having an inherent contrast of 100%. Many astronomical objects, particularly planetary surfaces, have a much lower inherent contrast. For an object contrast of 10%, curves 3 and 4 show the image contrast as seen in the telescope.

Regarding the resolving power of the combination of a telescope and the eye, we can now draw a number of conclusions from Fig. 9:

- the resolving power is higher for brightly illuminated objects than for dimly illuminated objects. Compare points F and B.
- the resolving power for high contrast objects is higher than for low contrast objects. Compare points F and G.
- for high contrast objects, for example double stars, the resolving power of an obstructed system can be slightly better than for unobstructed systems. Compare points E and F.
- for low contrast objects, for example, planetary detail, the resolving power of the obstructed system will be less compared to an unobstructed telescope. Compare points H and G.

This situation occurs as soon as the inherent object contrast is so low that the crossover point P and P′ [prime] falls below the contrast threshold curve. This conclusion is confirmed by the experiences of Pickering and Dall: "For the observation of low-contrast extended details, an unobstructed telescope is superior to a telescope having a central obstruction."



Summary

- Both resolving power and contrast transfer are quality criteria for any telescope.
- The accumulation of diffraction effects and the imperfections of the optics finds its expression in the position of the contrast transfer curve with respect to the idealized curve. The CTF curve can give a good overall picture of the telescope's optical quality and yields much more information than the testing on double stars can.
- The contrast transfer curves have a great instructive value because the behavior of the eye/telescope combination for parameters such as object brightness, contrast, obstruction ratio, and image aberrations can be clearly shown.
- For visual observation of extended details, it is difficult to define a precise resolving power for a telescope because parameters such as image brightness, contrast, and acuity of the individual eye must be taken into account.
- Any definition of resolving power is subject to strict conditions.

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■

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6. "Reflectors versus Refractors," Pickering, *Amateur Telescope Making*, Book 2.

7. "Diffraction Effects due to Axial Obstructions in Telescopes," H.E. Dall, *Journal B.A.A.*, Feb. 1938, page 163.

8. "Instruments a Pupille Annulaire," *Revue d'Optique*, no. 5, 1953, page 272.

Building a Kutter 3-Mirror Tri-schiefspiegler

by A.L. Woods

There is no finer reflecting or catadioptric telescope than the Tilted Component Telescope. For lunar and planetary observing especially, their owners (both in this country and in Europe) constantly extol their excellence. The one most widespread TCT design in use is the Kutter Schiefspiegler. A description on a small, all-spherical design appeared in TM#1, page 4, while a large catadioptric TCT appeared in TM#4, page 8.

However, many workers find making a long focus, wedged correcting lens, which is necessary in sizes over 4.25", quite difficult. In the late 1950s, while I was in correspondence with Anton Kutter, he mentioned that he had once tried to work up a design with just mirrors instead. I continued to press him to further investigate this type of Schiefspiegler. In 1966 he wrote that his research had been successful, but it was nine years later that the first details of the design were published in *Sky and Telescope*, January and February 1975 issues.

A number of people have built the Tri-Schiefspiegler, including a St. Louis, Missouri amateur, Al Woods. His 6-inch was pictured, but incorrectly captioned, in TM#10, page 29. (The correct caption appears on page 27.) For its aperture, Woods' TCT is the most enjoyed instrument at local star parties and is always in use.

However, the size of the Kutter 3-mirror TCT is limited by higher order aberrations. Although it was orignally designed to be scaled to apertures as large as 10", the limiting aperture is more safely and realistically 8". A 12.5" Kutter Schiefspiegler shown at the 1979 Stellafane has been abandoned by its makers as they were unable to obtain satisfactory performance from it.

Computer analysis by optical designer David Stoltzmann, the author of articles in TM#10 and TM#12, has shown that an 8", if made to specifications, will be an excellent telescope. The late Leland Barnes of Cal-Astro made commercial three-mirror Schiefspiegler sets with apertures up to 8".

Specifications

Dimensions for 6" and 8" Kutter Tri-Schiefspieglers and the optical layout for the tilted optics are given in the table on this page. Note that the angles of the central light ray remain the same in both examples and only the spacings and mirror sizes change. Both systems are f/14.7.

Requisite for good performance is that the radii of the mirrors must never be less than specified and all tolerances be on the longer side. It is also important that the figures be exceptionally smooth. Long radii, especially on the tertiary mirror, present a problem in this respect. Most of the Schiefspiegler instruments that workers were unable to finish were abandoned because the makers were unable to obtain a satisfactory smooth surface. It is now apparent that the Schiefspiegler is not an instrument for the beginner to make and that at least some prior optical fabrication experience is required to insure success.

Hints on Optical Fabrication

All light cones, whether at the focus or the center of curvature, have, due to the nature of light, a focusing tolerance zone along the optical axis in which all the light rays fall within the Rayleigh limit of ¼-wavelength error. The formula give by Rayleigh is:

$$T = \text{lambda}/N'\text{Sin } U'$$

where lambda is the wavelength of light, N' is the refractive index of the medium in which the light is traveling (for air, N' = 1.000), and U' is the angle from the top of the mirror to the optical axis. Substituting the focal ratio rather than U' into the formula, and assuming the wavelength of light to be 0.000022", the formula becomes:

$$t = 0.000088 \times (f/)^2$$

When applied to the Tri-Schiefspiegler mirror set, we find the tolerances at center of curvature to be: $R_1 = 0.036$, $R_2 = 0.77$", and for R_3 it is a huge 2.36"!

The tertiary mirror sagitta is so small that the curve can be ground in with fine abrasives; 22 micron grit should be sufficient. A smoothing abrasive can also be used for the secondary; 63 micron grit will probably do. (For screen size equivalents of abrasives, the reader should see the tables in TM#2, page 9.)

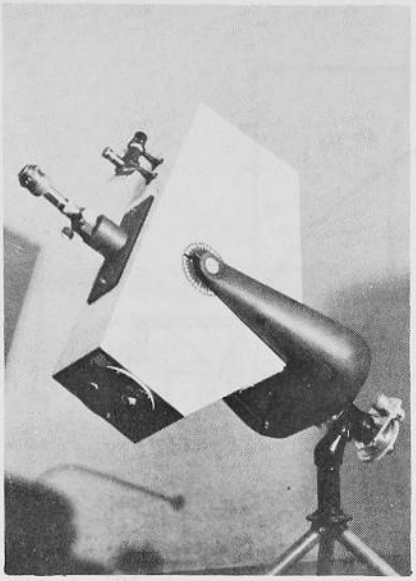
The shallow depths of the secondary and tertiary mirrors make radius control for these mirrors very critical — a real challenge for the maker.

In polishing, good contact and short polishing spells will help hold smoothness, especially if a harder than normal pitch lap is used. Frequently inverting the mirror and tool will also help both radius control and a smooth spherical figure. For the 6" and 8" instruments, the primary has a 53% correction (it is finished as an ellipsoid) to further improve the field of good performance.

Testing the mirrors will require some kind of auxiliary telescope for viewing them, as the angles they subtend at center of curvatures are so small. For R_1, it is about 1.5°, for R_2 about 0.5°, and for R_3 only 0.1°. A finder telescope or similar device will work just fine for this purpose.

Due to the three reflections, with regular 88% reflective aluminum the telescope will transmit only 68% of the light entering the instrument. It is recommended, therefore, that you put enhanced aluminum or silver on the mirror surfaces. Enhanced aluminum, at 94% reflectivity, will yield 83% overall, while silver at 98% results in an efficiency of 94% — better than a single aluminum coated mirror!

For either the enhanced aluminum or



silver coatings contact Liberty Mirror, Brackenridge, PA 15014 for the latest prices. In 1981, for the #756 aluminum coating (94%), a 6 inch was $24.20, and an 8 inch priced at $39.12. Their 98% silver, #950, with a protecting overcoat was $39.12 for a 6″ and an 8″ was $53.24. Under 4.25″, #756 is $12.72 and silver is $27.16. There is a minimum charge of about $50 — but the three mirrors of the Tri-Schiefspiegler will exceed this anyway.

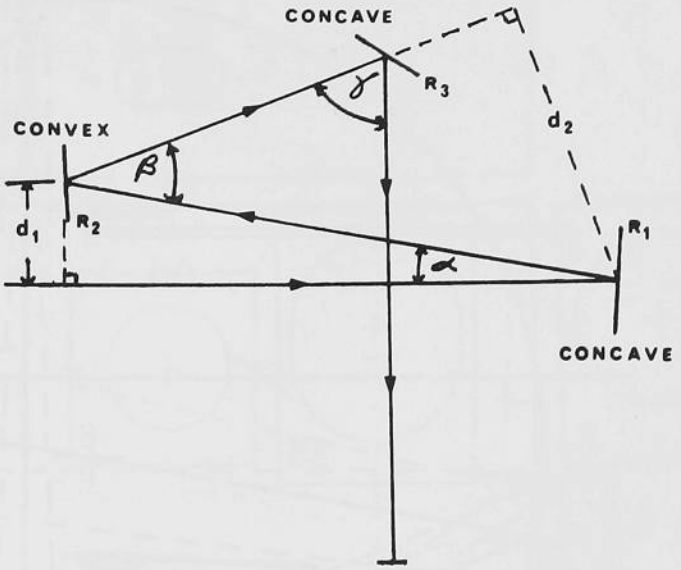
Robert E. Cox

Building the Tube

The "tube," container, case, or what-have-you that holds the optics for a TCT calls for more detailed planning than is required for non-tilted designs. The price for eliminating the diffraction effects of a central obstruction is tight tolerances in the placement of tilted optical surfaces which generate and cancel large amounts of coma and astigmatism. Hence tilted mirror systems necessitate more exact mirror adjustment in tilt, meridional centering and spacing, and these must be seriously planned for.

The multi-sided box or case must be solid, offer complete accessibility to and adjustment of all three mirrors, and at the same time be light and compact enough for almost any type of mounting. Such a case may be made with only saber saw, drill, and a few fix-it hand tools — and, of course, a sturdy flat table (ping-pong, anyone?) big enough for making the paper patterns and assembly.

The following "how-to" procedures are the result of my experiences with two such telescopes, both of which have given satisfying performance. The first weighed 26 pounds, but the second only 19.



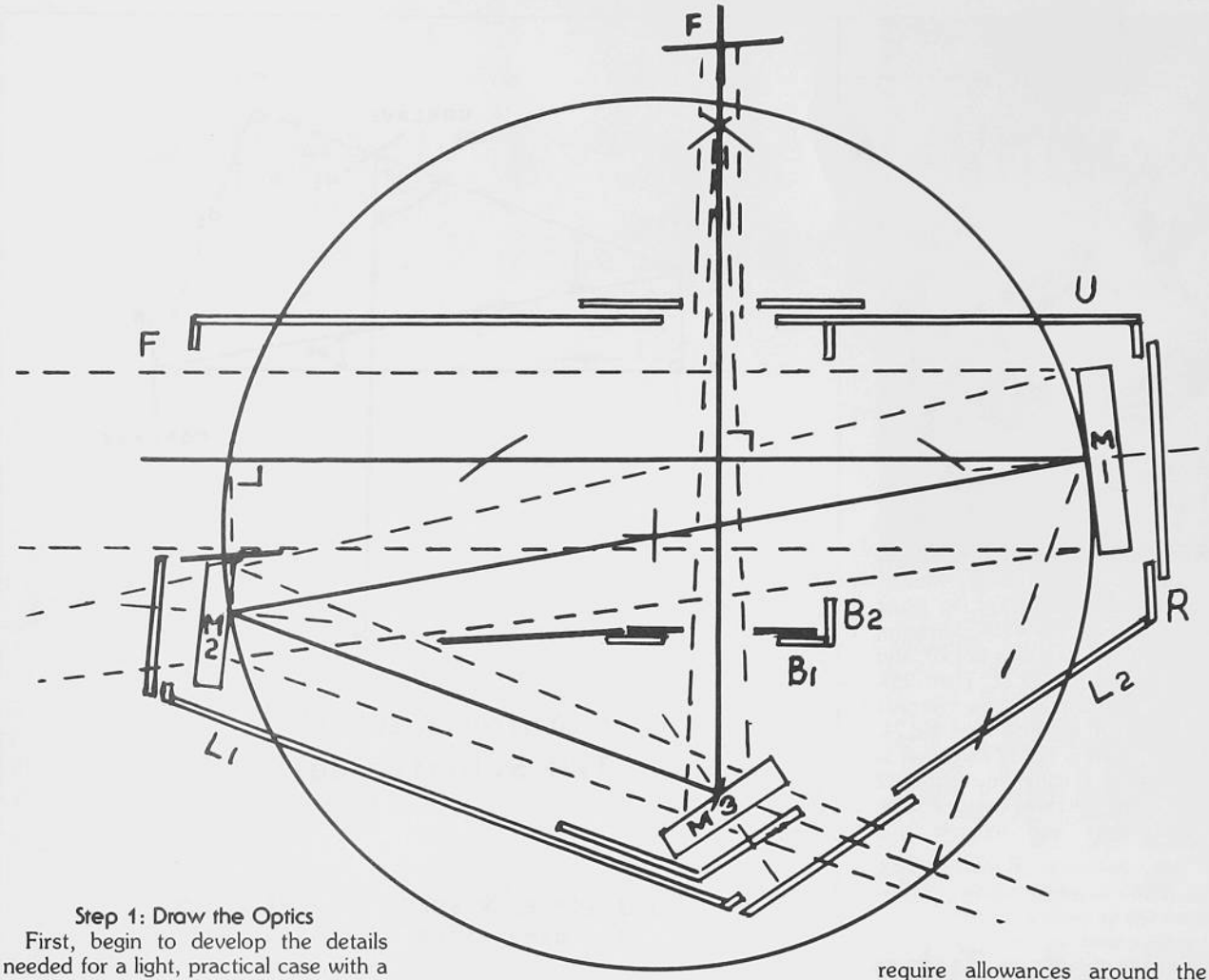
Anton Kutter's Tri-Schiefspiegler

TRI-SCHIEFSPIEGLER SPECIFICATIONS
(All dimensions are in inches)

Diameter Primary	6.0	8.0
Radius Primary (R_1)	121.95	162.6
Separation	30.38	40.5
Diameter Secondary	3.35	4.47
Radius Secondary (R_2)	177.99	237.21
Separation	18.40	24.54
Diameter Tertiary	3.35	4.47
Radius Tertiary (R_3)	982.3	1309.8
Back focal distance	26.37	35.16
d_1 (construction aid)	5.44	7.26
d_2 (construction aid)	15.38	20.50
Equivalent focus	87.91	117.2
Length of telescope	34.88	46.51
Focal Ratio (f/)	14.7	14.7

TILT ANGLES

α	10° 18' 46.8"
β	39° 25' 08.4"
γ	69° 53' 34.8"



Step 1: Draw the Optics

First, begin to develop the details needed for a light, practical case with a full-size master layout drawing of the optical system. If all the mirrors are close to their specified curvatures, proceed to add to the original drawing positions the outline of each mirror in the angle its face assumes in reflecting the central light beam. If the radii vary somewhat, and you followed Kutter's test set-up to find changes, use the positions as modified by your tests and revise the drawing.

Draw the incoming light path centered on the primary mirror, M1. Next measure on the central light beam from M1 through M2, the back focal point of M1 (one-half its radius of curvature). Assume an image size of 0.75", about one-third larger than the image of the Moon would be for a single-mirror scope. Draw the marginal edge rays from M1 to this image. Where these lines intercept the face of M2 is the minimum diameter of the mirror. If you used a standard 4¼" blank for M2, and if it is to be centered on the beam, it will extend into the path of the light going toward M1. To avoid this, offset M2 so that its upper edge extends only as high as the edge ray you drew. The edge of this mirror may be given a flat 15° bevel, providing it approaches the face no closer than ¼", to cut its silhouette and leave more room for placing the light baffle.

Next, calculate the back focal point of the two mirror combination, which is behind M3, the tertiary, from the multiple mirror formula. It will be about 28" behind and have an image size approximately 1.1". Draw the edge rays from M2 to this image passing thru M3. This plots the edges of the beam M3 reflects to the eyepiece. M3 is an oversize mirror centered in the beam.

Finally, draw the beam from M3 to the focal position. This path is perpendicular to the axis of the incoming light. Use the multiple mirror formula again, this time for the three mirrors, to locate the final focal point. It should come out about 26" from the center of M3. The final image size is about 1.05", which will just be fielded in the draw tube of a 1.25" focusing mount. The edge rays indicate minimum clearance for the baffle and the size of the opening on the top deck of the case. These two openings should be made enough larger to allow the use of a 2" focusing mount.

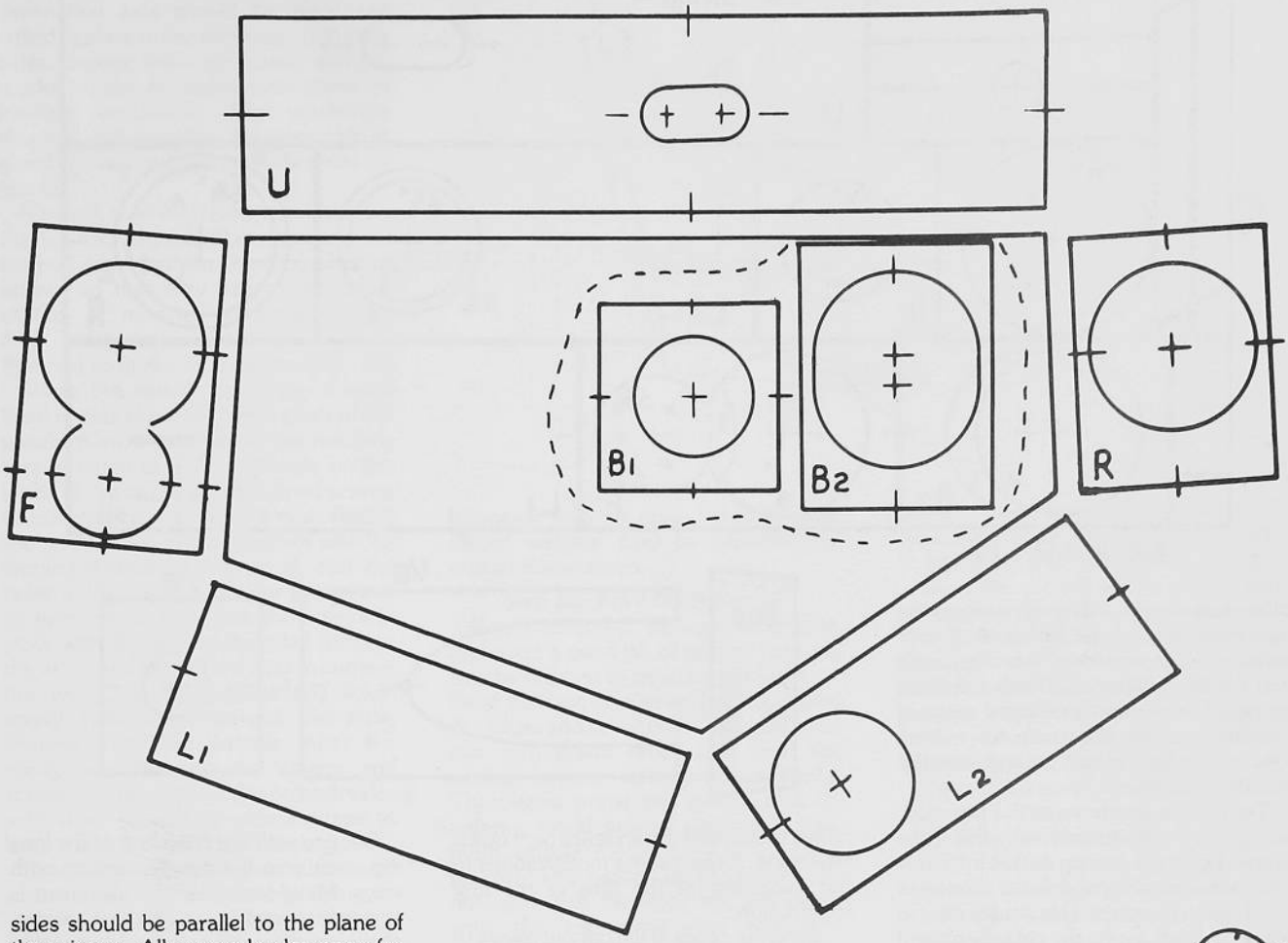
Step 2: Draw the Case

The light paths dictate the minimum internal size, shape and openings of the case. Practical considerations now require allowances around the light beams, space for mirror cells and mountings, and extra space for probable adjustments. The more exactly you know the positions of the mirrors from a test set-up, the less allowance you'll need to provide for adjustments.

Begin by designing the mirror mountings. Draw in the positions of the mirror cells and adjusting screws, springs (if used), and adjusting nuts. Provide enough extra space to allow outward adjustment of M1 by 0.75", M2 by 1.0", and M3 by 1.5". I suggest mounting of the M3 cell on a sliding carrier — this will require a little more space, but assures you can move it without changing its angle relative to the light beams, and is most useful in minimizing coma.

Review "Better Mirror Cells" by Robert E. Cox in TM#6 to see how best to mount mirrors. One of my telescopes has orthogonal mirror mounts, the "L" configuration that Cox describes. These mounts permit mirrors to be removed from the case for cleaning without disturbing the adjustments. See the section on mirror cells below.

Draw the inner wall outline of the case. Two of its sides must be parallel to the center beams of the light path, and three

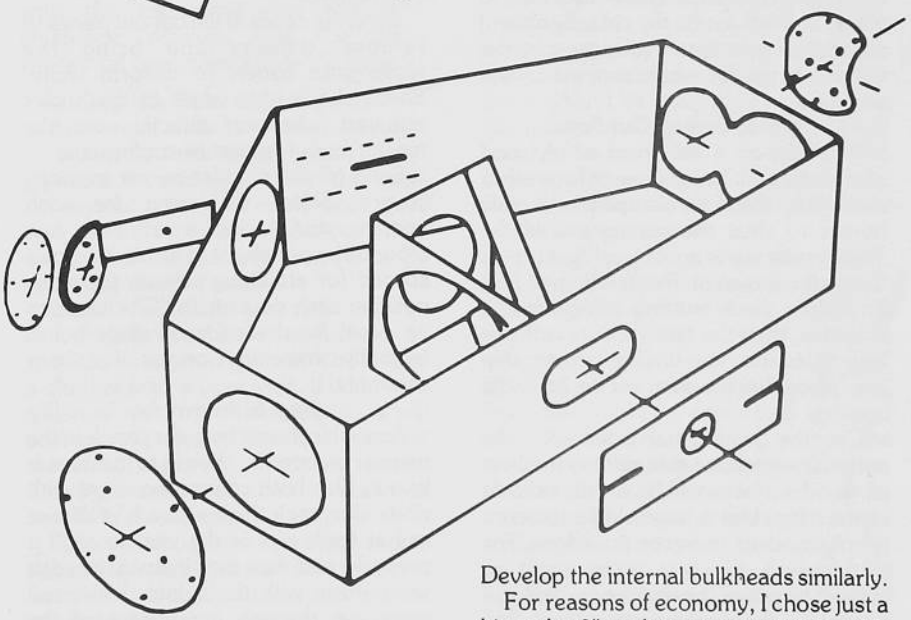


sides should be parallel to the plane of the mirrors. Allow ample clearance for mirror cells. Next, add the thickness of the plywood — ¼" — for the rectangular sides. Mark the openings, the size of the covers, and where the mirror supports penetrate. Determine the best fit for the angle joints of these panels so allowance can be made for cutting.

The same range of front-to-back adjustments allowed for M3 is applied to the opening on the top deck where the focusing mount slides. It is best to elevate a short 1.25" focuser with a section of larger tubing or a box to fit it to the slide rather than suffer vignetting from a longer than normal draw tube. A 2" focuser will mount directly and support a longer draw tube. The 2" focuser is preferable — you get maximum field, it will take large eyepieces, and has more room for tilt and camera adapters — but it will add more weight. Draw in the placement of braces, internal bulkheads, and light baffles.

Step 3: Pattern Layout

The shape of the two matching pentagonal sides is now represented by the area on your drawing that includes the edge thickness of the rectangular sides. Each side of the pentagon gives one limiting dimension for the rectangular sides of the tube box. Project each of these five panels from the box and draw the openings. Center everything carefully in the meridional axis. Detail the exact amount and angle of the lap joints for adjacent edges.

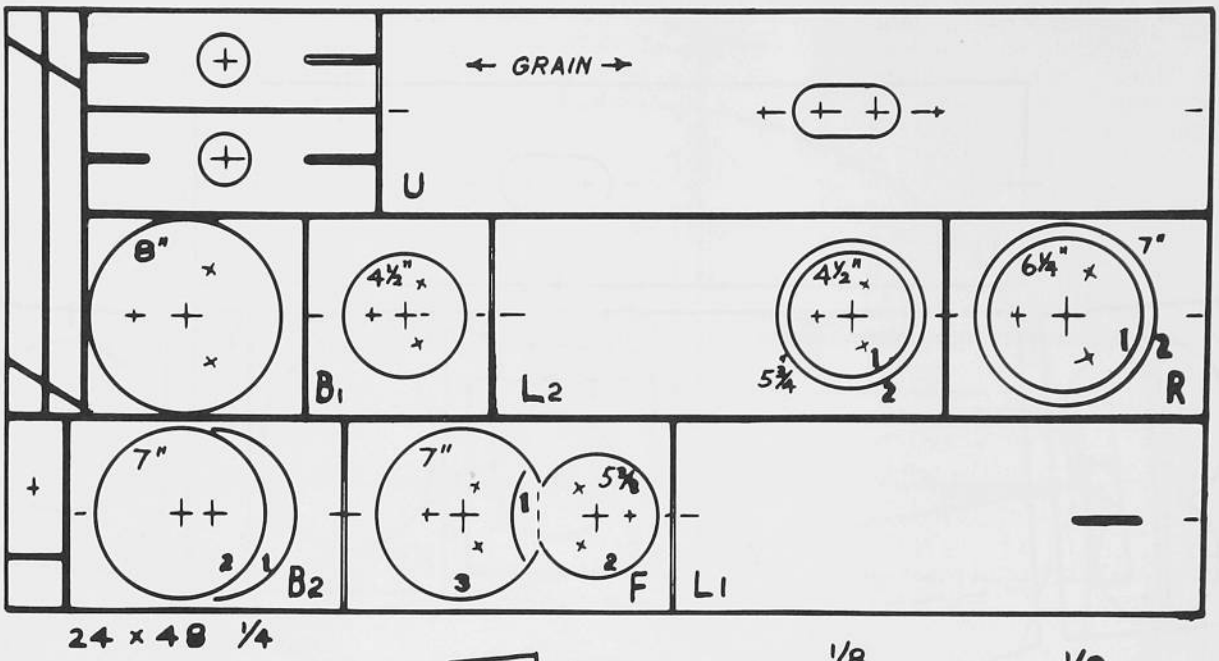


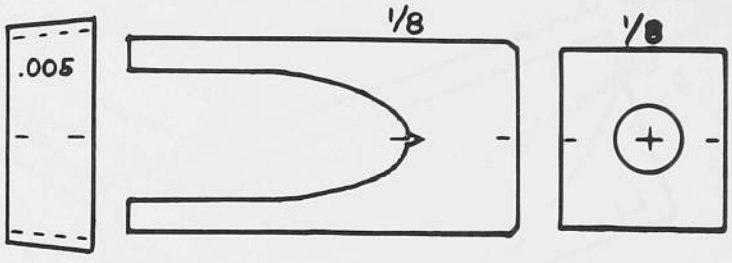
Develop the internal bulkheads similarly.

For reasons of economy, I chose just a bit under 8" as the common inside width of the case to get three strips out of a standard size plywood panel; this is ample for a 6" primary. Draw all details on your master layout.

Step 4: Transfer Dimensions

Select a sheet of exterior grade ¼" plywood, one side a good finish, the





other side sound with grain running the long dimension of the panels. A 24 x 48 inch sheet can provide all five side panels and the two bulkheads. Divide the sheet by pencil lines into three equal strips of material making allowance for cutting loss by drawing in two cutting lines the length of the sheet.

Transfer the patterns to the plywood, lining them up squarely with the three strips. Draft the cutting details for circle cuts, straight sides and extra allowance for shaping the joints. Use double lines to allow for stock loss in the cuts. By careful planning, you can salvage circular cutouts to use for mirror support-covers and cells.

Step 5: Cutting Out Parts

Working on a full sheet of plywood provides a built-in workbench for a saber saw. The sheet is clamped over saw horses to clear the cutting saw blade. The circular parts are cut out first (cut in the order shown on the drawing — 1, 2, 3) with a circle cutting attachment if available, then the straight cuts with the long sides. For the double circles, skip two places in the first cut to hold the centers.

Cut the pentagonal sides with the pattern flopped for one side so the best plywood surfaces will be on the outside of the case. Use a handy-knife to score ⅛" plywood to preserve the edges. For ¼" plywood, the two pieces might be tacked together, best sides in, and cut together. Sand the two panels to identical contours.

Two of the light baffles are cut from light ⅛" material, their pattern developed from the layout. The main baffle gets a notch cut in the meridional center edge of the opening to be used in collimation. The baffle over M2 is cut from 0.005" light sheet metal, and the ends are bent up for fastening. Expect some modifications to be necessary at the time of the first collimation.

Sand the edges of the cut-out pieces to remove defects and bring the rectangular panels to uniform width. Shape the mating edges to the angles required, checking directly over the master layout to assure conformity.

Sand off the circular mirror support-covers. Select the cover for each opening and swing a compass line around the periphery to locate six holes spaced for attaching screws. Carefully position each cover with "C"-clamps to its panel for drilling small guide holes. Indentify matching covers for later assembly.

Step 6: Assembly

Assemble the rectangular panels in the manner dictated by their fit to the master layout. Size both connecting edges with white glue, tack them with a ¾".#19 wire nail at each end of the joint to align it properly, and then tack it along the edge to conform with the layout. If the nail splits out through the surface of the panel, remove it and place another a short distance past the split area. Careful positioning of the nails minimizes this problem. Take extra care if the case will not be given a fiber glass covering. Avoid penetrating into any opening where the panel might be split.

Starting with the front end of the long top deck, join the panels working both ways. Make sure that the alignment is accurate to minimize warping, always checking that the outside contour matches the layout. Use both glue and nails — and don't be in a hurry.

When the five sides are joined into a five-sided ring, sand the edges at the joints to smooth out any unevenness. With the assembly free-standing on the "master," check the fit of the pentagonal panel. Tack it lightly to the assembly at each corner while drawing the edges to a fit on all sides. Small differences can be distributed without warping.

Gently remove the panel with the corner nails still in it, apply glue to a strip around it and to the matching edge of the assembly, reposition the corner nails in their former holes, and drive them in fully to hold it. Starting with the long top deck, proceed to line up each side's edge to a good fit and nail it down securely, spacing the nails every inch or so. Put weights on the panel to hold it flat on the table while the glue dries thoroughly.

There should be no warping of the assembled case. Check this, after it's dry, by turning it over and fitting it to the other side panel. Tack the second panel lightly at the corners. Do NOT assemble the second panel with glue and nails until the internal bracing and supports for the light baffles are installed.

The internal bulkheads that strengthen the tube box near the declination axis should be glued and nailed in place in the same way as the five sides. Square them accurately and put marks on the remaining side panel for locating bulkheads. The reinforcing diagonal stiffeners for the sides can be glued in after you determine the center of gravity.

You will, in all likelihood, need to move the ⅛" thick light baffles. Figure some method for attaching them by slots or screws so that they can be removed, shifted, or modified to accommodate final collimation. Install those slots trimmed to fit the internal bracing.

While the case is open, run a small bead of glue along the inside joints of the panels. Also, if you plan to use machine screws (such as 8-32) with nuts on the inside of the case instead of wood screws to hold the covers on, do it now. Redrill the guide holes in the panel to size for tapping threads in the wood, and the holes in the cover to size for the screws to turn freely. Now put the covers in place with the screws threaded through the wood and tighten the nuts to contact the wood. Apply quick-setting liquid epoxy (cautiously) around the nuts, keeping it off the threads. After the epoxy sets, remove the covers and screws and cover the holes on both sides with small squares of masking tape to keep threads clean while painting.

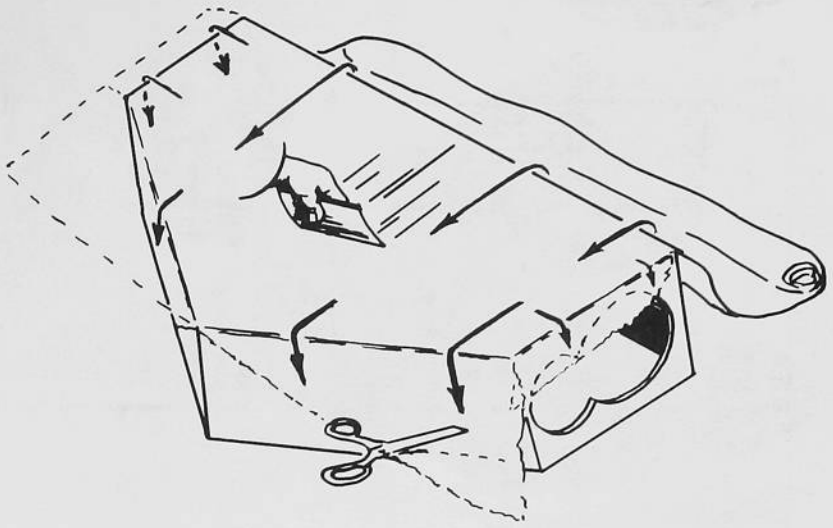
The last side panel is glued and nailed to the edges of the assembly, lining up corners, then edges and internal bracing. Weight it down flat on the table and allow the glue to dry overnight, then go around the inside of the joints with a small bead of glue.

This essentially completes the construction of the case. Making the focusing mount slide, the mirror cells and completion of the mirror supports will be deferred until after the balancing and finishing of the case is described.

Step 7: Balancing

Locating the center of gravity for installing the declination axes cannot be done exactly before all mirrors, focuser on its slide, and the finder are installed. But a satisfactory approximation may be made when the case is constructed and the mirrors and cells, baffles, covers, focuser and slide are ready. Lay the case flat on its large side over a broomstick or straight pipe. Tape each of the parts securely to the case over the position shown on the master.

Check the balance over at least three axes by shifting the rod or pipe and judging the balance points. The intersection of these lines of balance will be close enough that the stiffeners can be glued into each side and declination axis guide holes drilled. Mark the point exactly the same on both sides. Precise balancing may be done later, or small sliding weights may be installed for critical adjustments.



Step 8a: Paint Finish Option

If you've used ¼" plywood all around, and done a good job of nailing, the case may be finished to an attractive product. Sand the case all over and slightly round the edges and corners. Fill any voids and pits with plastic wood and sand the surface to your esthetic requirements. Thoroughly prime the outside with an exterior wood primer, sand well, then finish with a medium speed brushing enamel. The harder spray enamels do not yield with the wood and will crack with the treatment that well-used equipment receives. Use flat black interior oil base paint inside the case.

Step 8b: Fiber Glass Option

If you want a hard and tough finish for an unusually solid but light case, use ⅛" plywood instead of ¼" for the large pentagonal sides and apply fiber glass over them. The final finish and color may be applied by brushing enamels or by spray automotive finishes.

Glass fiber cloth and resin can be procured from a boat manufacturer or specialty fiberglassing firms. You'll need a cloth at least a yard wide. If you buy a gallon of resin from these places, it will cost you what two to three quarts cost at the auto, paint, and hardware stores. The light weight of cloth is easier to handle and sand out.

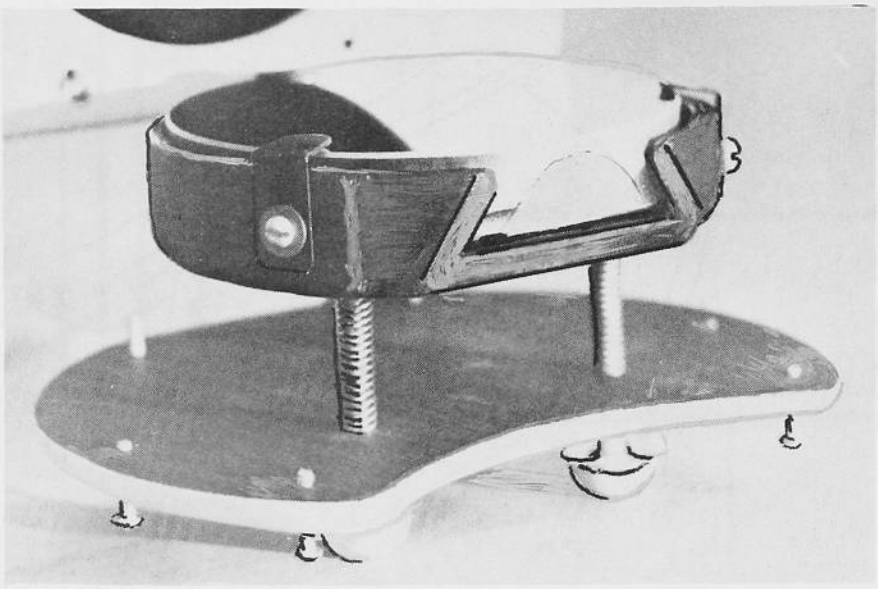
Before starting on the case, gain some experience with small batches of resin to learn how fast the resin sets and how the amount of catalyst controls the speed and time allowed to work. Be very accurate with the measuring, in drops! Mix no more than you can use quickly. Use clean containers for each mix and clean your brushes thoroughly. Keep the MEK or acetone solvents in closed containers out-of-doors and do the work outside. Making the mirror cells for the telescope is a good way to learn fiberglassing, and suggestions follow.

Give the outside of the case a good sanding and round the edges and corners slightly. Tap any protruding nail heads down and give the outside surface and all edges of openings, covers and focuser slide, a brush-coating of catalyzed resin as a prime coat. After it hardens, knock off any high spots.

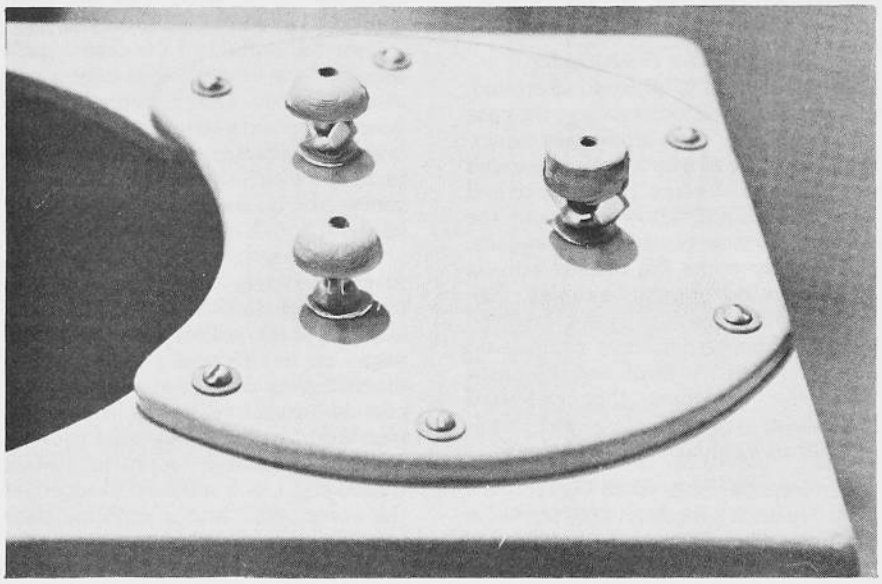
Figure on a piece of cloth long enough to wrap entirely around the case and wide enough to overlap half the ends. Lay the case on its large side and beginning at the edge where the side meets the top deck, give the side a fast coat of resin. Lay the cloth with the weave matching the edge, and coat the cloth with enough resin to wet it thoroughly. Use a stiff card to squeegee the excess resin and smooth the cloth (don't press too hard) to the edges at the bottom of the side and over the ends. Snip the cloth where it helps the cloth to lay flat without overlap.

Concentrate on a smooth contact, and keep the weave from popping up or wrinkling. Simply stretch dry cloth over openings — after the resin sets, it can be trimmed off neatly with a sharp knife. Then turn the case over and, continuing from the first edge, apply the cloth and resin to the top deck and across the remaining side, ends and bottom. Do not overlap the cloth. Trim off and use the excess to fill in spaces left so the entire surface has a complete cover and only small voids on the ends and bottom remain to be filled in. These can be filled by a local spotting of resin in successive steps.

Sanding and recoating with resin can proceed as far as desired. If power-sanding equipment is used, apply several heavier coats of resin first and go easy so as not to accidentally wear through into the wood — you are not building a boat.



The secondary and its cell



Step 9: Mirror Cells

Only part of a standard mirror cell is needed for mounting the mirrors, because support is supplied through the spring loaded screws and the covers giving access to them. The mirror part is made with glass fiber cloth and resin. The ¼" plywood disks are from cut-outs, and the bits of cloth are salvaged from tube box scraps.

For the 4.25" and 6" mirrors, save #10 juice cans and 3-lb coffee cans. A few turns of masking tape adjust the size of the closed end of the can and provide a mold over which resin-coated cloth and disk can be laid.

Cut the plywood disk to the size of the mirror blank plus at least ¼". You can cut a central 2" hole to lighten the disk and allow ventilation. Drill 3 holes 120° apart (or 90° apart if you want an orthogonal mount) at 70% of the radius of the mirror for 3/16" x 3" support screws, and drill matching holes in the support-covers. Use tape to bring the upper 1.5" of the can and plastic lid to the size of the wood disk.

Coat the edge and back of the disk with resin, then place it on top of the plastic lid, and wrap a 2" wide strip of glass cloth coated with resin around the disk and can. This will overlap the disk about 5/8". Fold over and flatten down to the back of the disk. Make cuts to relieve wrinkles. Coat another piece of cloth and lay it over the back to hold down the edge. Pat it down and keep it in place until the resin sets. Trim off any excess edging and recoat.

Successively apply at least three more turns of coated cloth strips around the can. Allow these to lap both ways with at least 1.5" extending down the side of the can from the plywood disk to form the retaining rim for the mirror. Set it aside to harden thoroughly.

Hint: To make straight cuts across the width of glass fiber cloth, pull a thread at the edge. This will leave a well-marked pucker trail which you can follow with scissors. These threads may be used for sewing or tying the cloth if necessary.

After it has set, pull and twist off the "cap" you have made. Trim and sand down any rough edges. Mark the depth of the rim to hold the mirror, then saw the cell off with a hacksaw and dress it with a file. Coat the entire piece with resin again.

The 6" cell should be reinforced 120° apart on the rim. Setscrews threaded through the reinforced sections bear against leather or hard rubber pads attached to the mirror. Make the threads for these screws when the mirror is installed. One method of attaching pads is to the side of the mirror with Pliobond or epoxy. Holes in the pads that match the setscrews in the cell will support the mirror without pinching it. Three more thin pads should cushion the back of the mirror over each support bolt. Held in this way, the mirror is gripped firmly, but has no obstruction at the edge.

Mounting clips may be used for oversize secondary mirrors since they can be placed so as not to obstruct any light. The clips can be anchored directly into the edge of the plywood disk or to a reinforced fiber glass rim. Small mirrors can be secured to a backing disk of the same size by wrapping several turns of soft plastic tape around the edge.

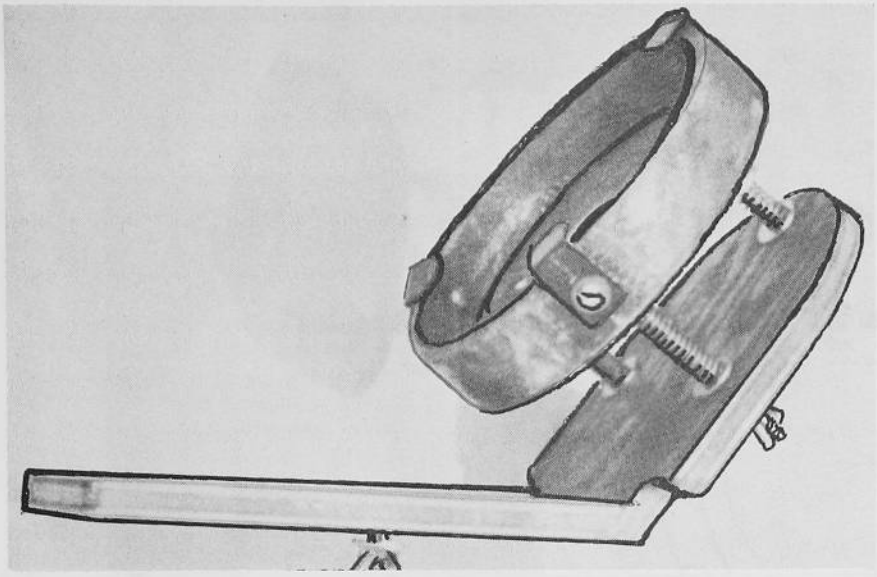
The cell for the secondary should be modified by removing a section of the top rim and back of the cell so that the mirror edge extends out of it, thus leaving a little more space for the light baffle.

Drill out and countersink the holes for the flat head support bolts (3/16" x 3"). These should be screwed down so the heads are below the surface. Smooth off and give the cells a finish coat of resin. They also need a coat of flat black paint; interior oil base coatings made for photographic darkroom walls or wrought iron flat black spray can lacquer work well. Latex or water-based paints should NOT be used.

Drill holes in the support-covers to allow the bolts to work freely. For triangular supports, the meridional holes should be centered and placed to match the mirror cells. (For orthogonal supports, make sure the meridional and sagittal planes are properly oriented.)

Cut compression springs of the correct length from spring stock available in about two foot lengths at hardware and craft supply stores. Select a size just big enough to slide loosely over the threaded bolt and compressible to half its normal length with a firm effort. A ¼" spring usually works over a 3/16" bolt.

Cut each spring about 1.5 times as long as its length under compression and



The tertiary is held in an angled fixed cell that can slide parallel to the optical axis.

file the ends flat. Mount it on the bolt between washers. Wing nuts may be used for adjustments, but they will need locking nuts. Make these from T-nuts. Clip off the prongs so the threaded section contacts the center of the wing nut and the flat disk bears against the wings. Oil the threads of the bolt and mold a knob on the outside face with a paste epoxy. Any excess length of bolt can be cut off after final adjustments of the telescope.

The cell mounting for the tertiary consists of a support panel attached to a strip that slides between guide rails. The strip has a short bolt threaded in it which moves in a slot through the bottom of the case. It is locked by a washer and nut. Later, after the final spacings have been determined, insert a small wood screw through the bottom of the case to fix its position for identical replacement.

Step 10: The Focuser Slide

Finding the exact focuser position is part of the final collimation of the Kutter TCT. It rides on a small sliding panel slotted at each end with a hole for the light at least 2″ in diameter. Cut two identical pieces and glue them together. If you're using a 1.25″ focuser, it should be the type with a refractor or Cassegrain-type base. Elevate it with a tubular extension. Focusers for mounting on round tubes can be used, but be sure to seal around it to keep out dust.

The slide is held with small bolts and wing nuts so it may be moved front-to-back as collimation requires. The flat surface of the slide invites adaptations for accessories mounted on additional slides. Prime the unfinished surfaces with resin. The top may be given a wrinkle finish from a spray can.

Step 11: Making a Tilter Adaptor

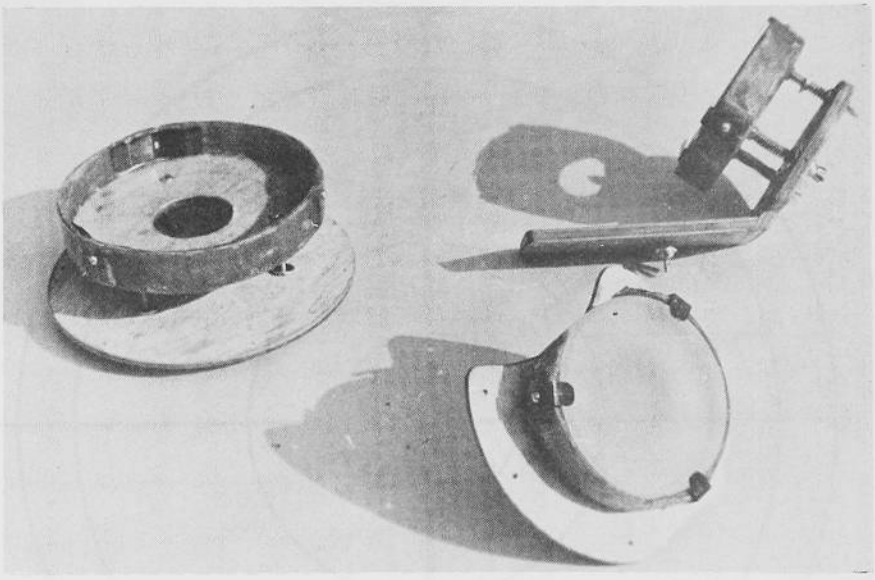
While not a part of the case, the adapter that holds the eyepiece at an angle to correct for the 4.5° focal plane tilt is an indispensable accessory to the system. You CANNOT get the right result by tilting the focuser — focusing then moves the eyepiece across the optical axis.

For 1.25″ eyepieces, modify a metal sink trap extension. At the point where the trap changes diameters, hacksaw almost through it. Bend the tube to the correct angle, then reinforce the inside of the tube with paste epoxy. Keep only enough of the small diameter end to give good support in the drawtube. In the larger end, cut a slit in the rim and compress to grip the eyepiece well. For 2″ focusers, a short section of 1.25″ I.D. tubing can be fastened inside a length of 2″ tubing at the required angle with heavy epoxy.

Stiff epoxy paste or putty (such as Duro brand E-POX-E two-part paste or ribbon) may be used to mold around the greased threads of a large Erfle eyepiece to join it at the desired angle to a 1.25″ or 2″ tube. Don't forget the grease, or it will be a permanent connection. Keep both grease and epoxy off of optical surfaces! When the epoxy has set enough to take the strain, unscrew the eyepiece.

When using epoxy, grease lightly wherever you DON'T want it to stick. Avoid using excess material that may flow or overlap. Work with small amounts at a time to build up large areas or heavy masses, then apply more after the previous amount sets. Support the work so the putty has only its own weight to hold up.

All three mirror cells



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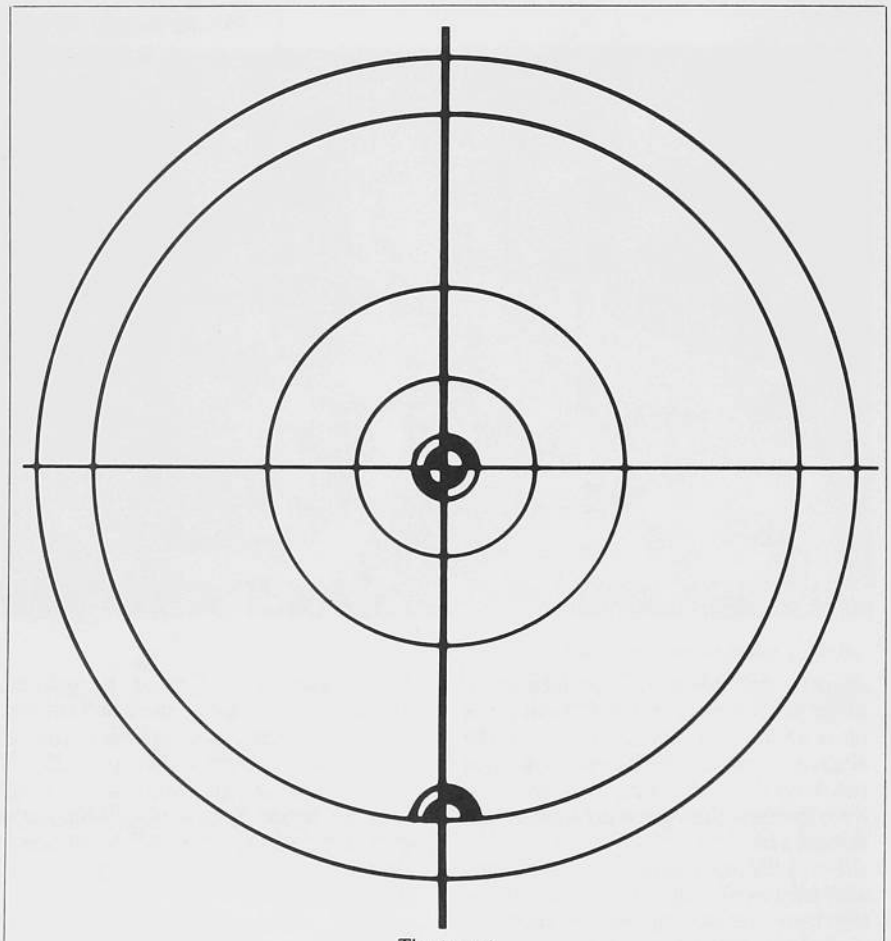
Collimation for a Kutter Tri-schiefspiegler



The target

The prospect of collimating a three-mirror TCT should not deter any amateur from building one. Yet it is certain that haphazardly twiddling adjustment knobs will lead to frustration.

However, with routine procedures and an understanding of which mirror reflects what, and learning how the tilts and spacings bring about the corrections needed, almost any problem can be greatly reduced or eliminated providing the mirrors are well made and well mounted. The following directions assume that the case is fork mounted with the meridional axis passing through the polar or azimuth axis.

References to adjusting "screws" in this article apply to machine screws fixed in or threaded into mirror cells which are adjusted by wing nuts turning on the screws, or the screwheads turning, against spring loading. Turning clockwise will pull the mirror toward the fingers. In systems where the mirror is suported by a fixed center bolt and adjustment is made by screws pushing against the cell, the action is just opposite.

Collimation is divided into three stages, each successive procedure requiring a little more patience, but yielding more satisfaction: 1) eyeballing; 2) targeting; 3) star-pointing.

Stage 1: Eyeballing

When the mirrors are mounted in the completed telescope case and set up with spacings to specs, or previous testing as noted on the master layout drawing, place the telescope on a solid table or in its mounting. Center the eyepiece focuser slide approximately over the tertiary (M3), then point the front opening toward a light wall or piece of sky.

Look through the empty focusing tube. Adjust the screws of M3 so that the secondary (M2) appears roughly centered. Then adjust M2 so that the primary disk (M1) joins the image of M2 centered near the top of M2. Now adjust M1 so that the light of the front opening reflects in M1 as a full disk. By now you are aware of the adjustments involved.

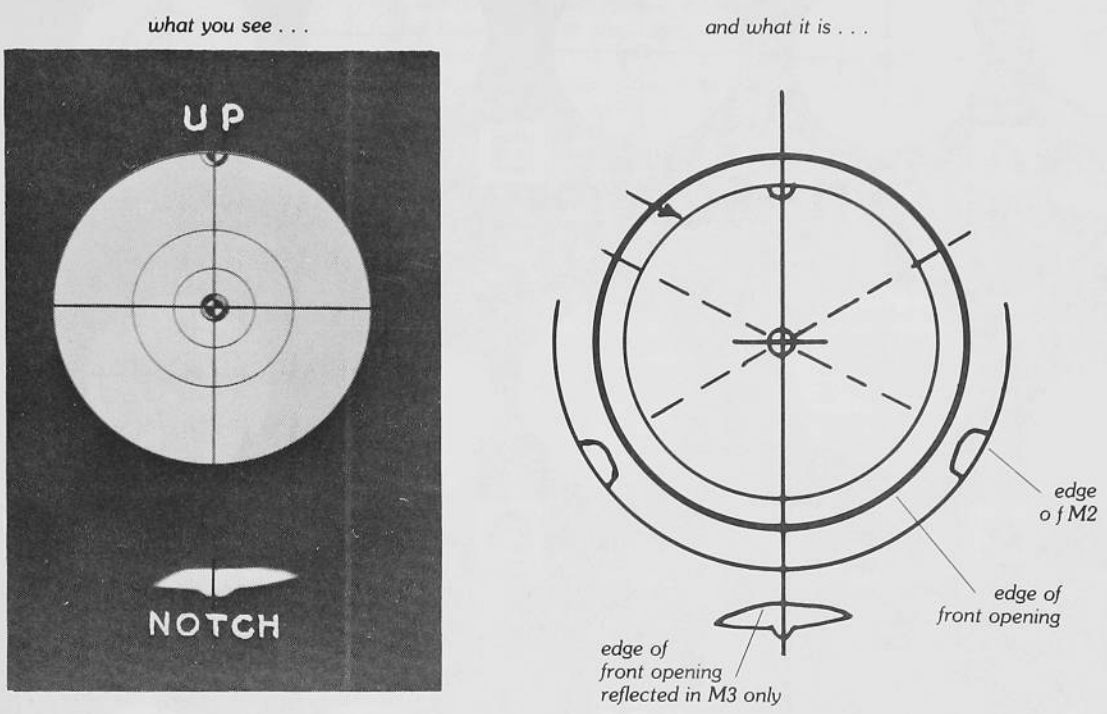
Stage 2: Targeting

In this stage, we'll improve the alignment by taping a translucent target over the front opening. This is made by drawing with India ink or dark pencil on frosted Mylar, tracing paper or thin typing paper.

The target consists of a vertical and horizontal line intersecting at the center of two circles, one the diameter of the objective mirror and the other the diameter of the front opening. Mark the bottom center point of the first circle to orient the reflected image.

Tape the target over the opening, the

Looking into the Focuser

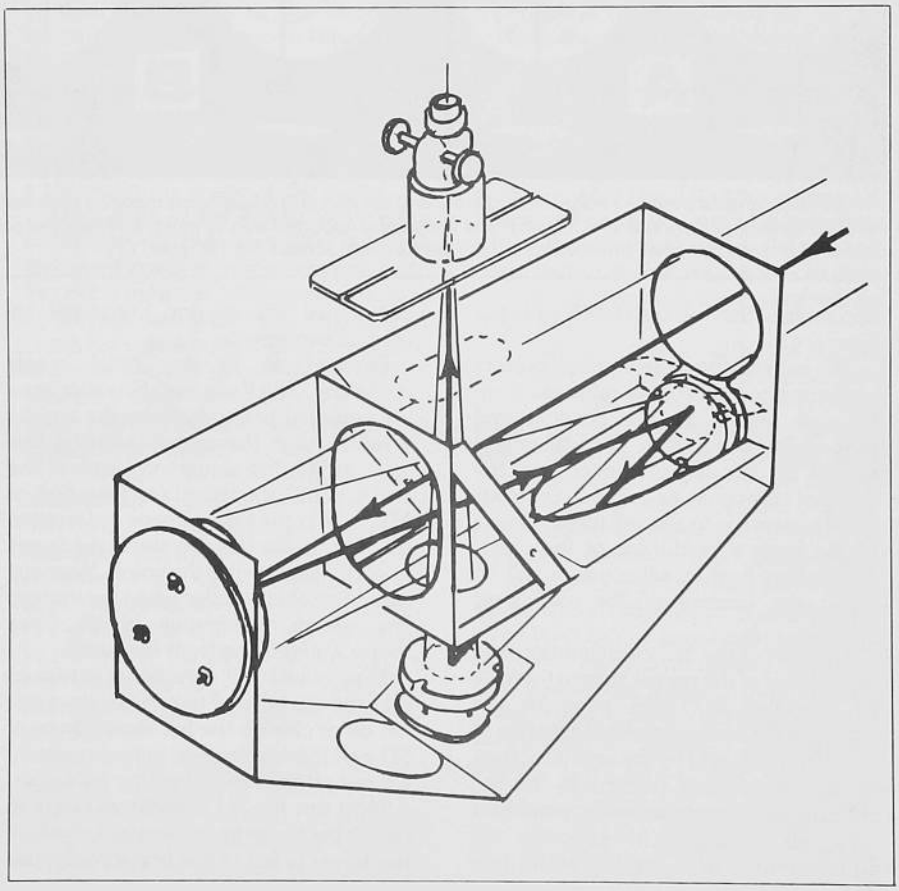


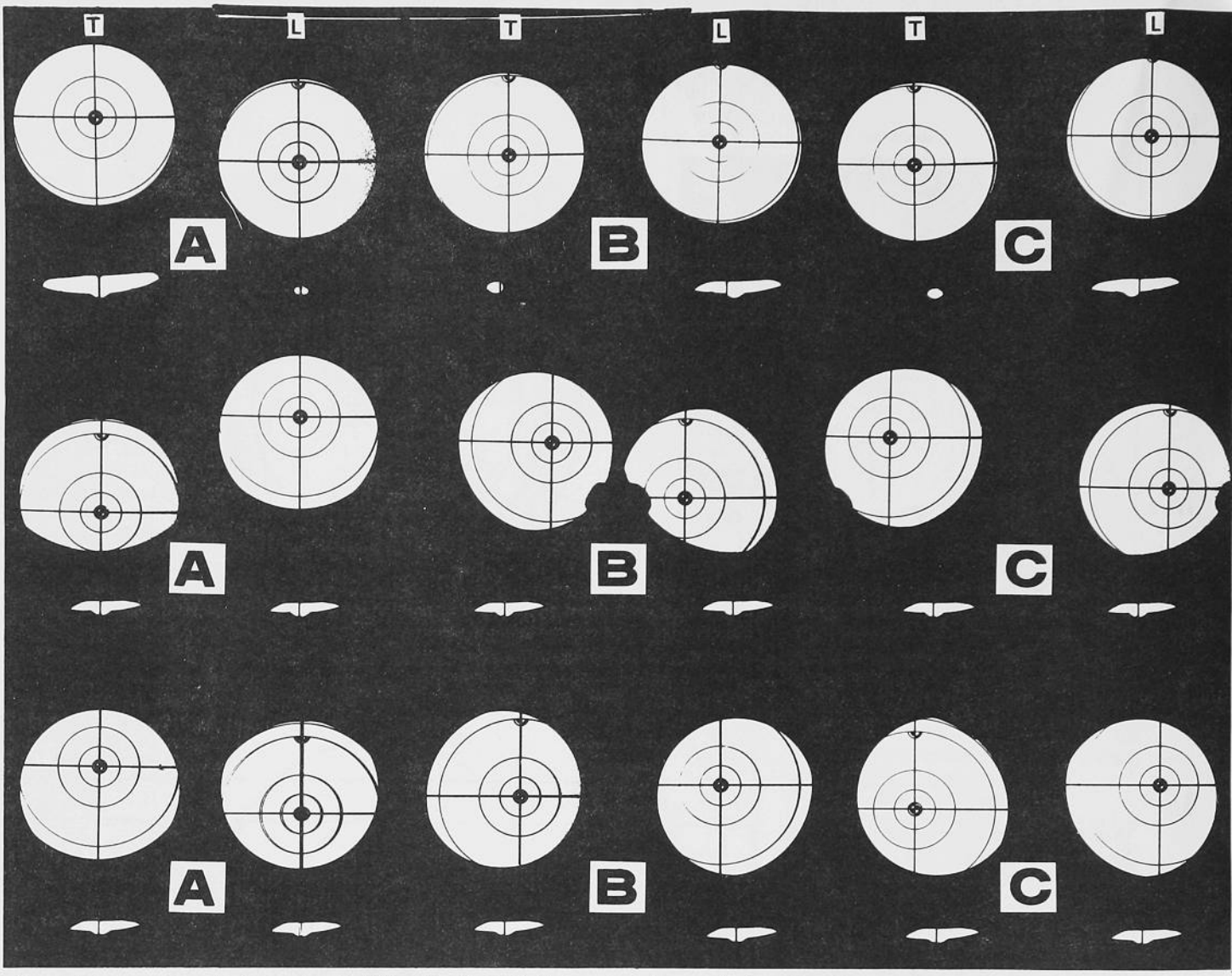
drawn lines inward, centering the vertical line to intersect the meridional adjustments of M2. Light the target well enough from behind to get a good image in the mirrors.

Insert a collimating eyepiece in the focuser tube. This will fix the eye position. If you don't already have one, make it from a short length of 1.25" O.D. tubing with closed ends, each having a ⅛" hole carefully centered, or a similar item made with an old 35mm plastic film can.

Standing behind the primary end of the telescope, look into the telescope through the collimating eyepiece at M3. The target will show in the light disk and "up" is related to the adjusting screws of the mirror supports. Tightening the meridional screw will pull the center of the target toward that screw, but tightening a sagittal screw will move the center of the target toward its opposite side. This is indicated in the diagrams.

For orientation, you should see a notch in the meridional centerline of the main light baffle in M3 "down," or toward M1 as in the illustration, if a little light is allowed over the M2 baffle and the main baffle is cut out enough. If your baffle does not have some such reference point, add one — something like a nail or pin — to the corresponding centerline to be caught by the periphery of M3 to





These photographs show the image viewed in M3 and the effects of adjustments made on each mirror. These images are viewed through a diagonal which inverts the image and apparent axis of motion. Meridional screws are those in the plane of the centers of all three mirrors ("A") and sagittal screws are "B" and "C".

accomplish the line-up of M3 with the eyepiece.

The pattern and movements of objects appearing to the eye as reflected from M3 are related to the position and purpose of each mirror. The adjustment screws tilt the mirrors to control the paths of reflections as in the chart. Your initial concern is to align all three mirrors to the vertical centerline of the chart. Thereafter, further adjustments will be under the control of the meridional screws.

The use of the "L" configuration in a remodeling of the mirror support screws as described in TM#6, page 34, will eliminate the confusing oblique motion of the mirrors caused by the sagittal screws of the conventional pattern. In the "L" pattern, the corner screw is employed only for changes in spacing; tilt adjustments are made with two orthogonal screws for horizontal or vertical centering.

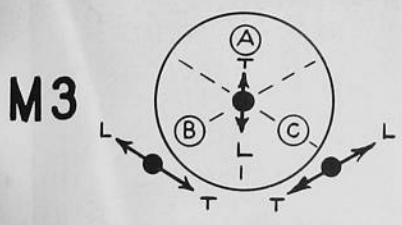
Proceed as in the initial rough eyeballing. The three variable reflections are centered horizontally by the sagittal screws. Align the target's vertical line with: in M3, the centerline notch of the baffle; in M2, the reflection of the disk of M1; in M1, the target image centered in the disk. In the last two steps, the target line is that indexed in the notch. Your eye should be able to judge when the vertical line seems continuous in all three mirrors, extending from the notch.

Now adjust M2 meridional screw so that the top edge of the mirror does not cut off or change the full round shape of M1 as it moves closer to the index notch. Do not attempt to line up the full target.

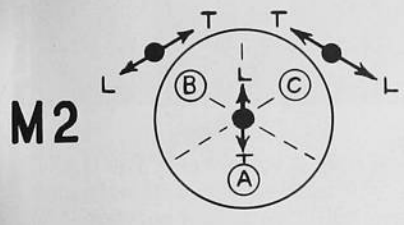
Next use the M1 meridional screw to center the target image vertically in M1. If the target is out of line horizontally, use the M1 sagittal screws to move it. Note that none of the adjustments on M1 or M2 moves the vertical line indexed in the notch by M3. The target should finally appear as illustrated after being "squared on."

The emerging light path must exit at right angles to the "top" deck of the telescope, so remove the focuser slide so that a square may be used to locate the position where the focuser should be centered.

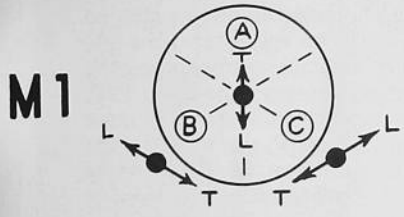
If any vignetting or block-off of the target appears after the slide is repositioned, check for encroachment of a light baffle and modify its position or size. A re-adjustment of the M3 meridional screw and re-squaring the focuser should clear this. Another check is made by sighting down the interior walls of the draw tube to observe that an equal amount of the target image seems



The notch and lines indexes, the primary disk, and target all move. "L" and "T" mean loosen and tighten, respectively.



The primary disk and target move. All "B" sagittal screws are on the same side of the case.



Only the target moves.

cut off by the tube on all sides. Your scope is now "on" for one axis.

You will, at this point, obtain considerable satisfaction by standing ten to twenty feet in front of the telescope opening to view the concentric reflections from the three mirrors of the small light disk of the focuser tube opening.

Focusing with a low-power eyepiece against a distant brick wall or focusing on a bright sun reflection from a spherical polished surface a few hundred feet away may give you a rough idea of how close to right-on the image is shaping up. But only points of light at infinity can give you the final targets, and allow you to correct the images appearing through an eyepiece.

Stage 3: Star-Pointing

This last step may have to be broken into a number of sessions depending on the availability of good seeing. A lot will be gleaned concerning the limitations of reassembling the bits of light energy from space into intelligible images through fine-tuning your optics. Recognize that the out-of-focus diffraction images are trying to tell you the limitations of your instruments and of the atmosphere.

Seeing can change drastically and rapidly — so don't expect your telescope to correct for miles of misguided light rays. When favorable changes occur, enjoy them, but cover your scope before you change any setting when seeing goes sour.

For the first night, you can get by with fair seeing. Set up the telescope on its mounting, insert a 100x eyepiece, and locate a first or second magnitude star. If mirror spacings and previously cited collimation are anywhere near good, the extra-focal image has a good chance of having an elliptical shape. Even if a high degree of astigmatism remains and you can get only a horizontal or vertical line focus, progress has been made.

If the astigmatism does not lie in one of these axes, the first adjustment to be checked is the sagittal screws of M1. Turn one of them whichever way rotates the line focus closest to the vertical or horizontal position. Try in and out focus.

Then adjust the M1 meridional screw in the direction that shortens the line into an elliptical shape, and the elliptical more to round. Choose an out-of-focus position so the astigmatic ellipse appears vertical. Adjustment by the meridional screw causes the image to travel along the vertical axis and become rounder.

Whenever the diffraction image appears to be nearly round, check your eyes for their own astigmatism. Judge if different positions of your head produce a change in the shape of the image.

On a night of fair seeing, reduce the extra-focal distance so a 200x eyepiece shows an image of only a very few rings. Breaks in the outer or faint rings, or more light in one side of the edge ring, indicate coma is excessive and needs correction. Coma is a consequence of the oblique light path, much as that observed in low focal ratio paraboloid systems as the image drifts off-axis.

Correction of coma along with astigmatism is controlled by the tilt of M3, and the amount of correction increases with the area of the light cone reflected. If the coma appears on the edge toward the front, or "up" as viewed in the eyepiece, it is not fully corrected, so the area of the light cone reflected by M3 must be enlarged. Therefore, decrease the space slightly between M3 and M2.

The sliding mounting for M3 was designed so the mirror distances can be changed without materially altering the angle of M3. The spacings of the other mirrors may be changed by turning all three screws on a mirror the same amount in the same direction.

Wing nuts provide a good indexing control and may be "locked" by knobs screwed over them. It is also suggested that the meridional screw or nut be equipped with a locking knob of distinctly different feel so no confusion is invited with a sagittal screw.

After shifting the position of M3, or making large changes in adjustment for the shape of the image, center the focuser, eliminate the astigmatism by the meridional screw of M1, and re-examine the smallest diffraction image for improvement, and, if it is better, whether any more is required. When the coma is satisfactorily reduced to a minimum, if not eliminated, and the smallest Airy disk is obtained in good seeing, test for any improvements by applying very small adjustments with the meridional screws of M2, and then, separately, M3. If you see no improvement at either point, return the adjustment to where it had been.

The star image in a tight diffraction disk will change shape and size slightly as it moves across the field along the vertical axis from back to front. It is changing in focus because the focal plane is tilted. This may be corrected with a "tilted" eyepiece. Kutter's design calls for a tilt of 4.5° to match the focal plane. Use an adapter, do not tilt the focuser, to make the correction. The performance difference is quite noticeable.

Since there is no central obstruction to overcome or support spikes to appear in the diffraction image, you'll have more visual sensitivity in seeing aberrations and defects often lost in the confusion encountered in Newtonians. Take seriously what the diffraction pattern is telling you, and you may be surprised what defects can be isolated and corrected to enable your optics to yield the excellent performance potential of really good TCT.

A daylight check with the target carefully placed, and a squared-on look down the draw tube, can assure you that there are no misalignments due to sagittal error or cut-offs in the light path. When the adjustment screws are locked, there should be no changes of any extent required over a long period of time. The mirrors should be installed so their entire mountings may be removed for cleaning without any disturbance of collimation other than can be corrected by a touch. Any slight adjustment needed thereafter can usually be easily made in dark conditions. This system is not temperamental, and is a great one to enjoy.

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1982 RIVERSIDE

self portrait in a concave mirror

More than a little frazzled, I'm sitting in a Jack-in-the-Box drive-thru restaurant in some tacky suburb of Los Angeles. The sky is grey, the clouds hang low, the air is chilly, humid, polluted and smelly. Visibility is about one-quarter mile. The mountains are hidden. Signs hanging over the intersection say "Waterman Ave" and "Baseline St."

I munch down a soggy cheeseburger, take my noontime antibiotic, then wash it down with Coke. "I'm halfway to Riverside," I think to myself; "the flying is over but there's driving yet to do." The next stage is driving up into the mountains to Big Bear and then Camp Oakes. And I'm surprised to find myself here.

I hadn't thought I'd make it. Three weeks earlier, I'd caught a head cold, which developed into a chest cold, then bronchitis, and finally a high fever with pneumonia. For a while it looked like I'd have to cancel the plane reservations, cancel the rental car, cancel the trip, but the pneumococci had yielded to the antibiotic, and aside from a residual cough and considerably diminished get-up-and-go, I seem okay.

It's time to get going. I look outside, and it's started to drizzle.

Up the mountain I go. Even under the dull skies, the hills covered with bright yellow flowering bushes seem infinitely better than the city. At 3,000 feet, cold and drizzle give way to cold and thick cloud, but at 5,000 feet the fog begins to brighten. Suddenly, just past the 5,500 foot marker, I drive into clear bright sunshine. Blue sky. The air smells good, of pine. The sun warms my legs and lap and the car seat beside me. My tiredness vanishes.

An hour later I turn off highway 38 and drive the final miles into mostly deserted Camp Oakes. I park near the dining hall.

The Big Bear IAPPP crew, Don Rohe photo.

Standing in front is Pete Manly. "This is the place. I'm really here!" I walk over, and he says, "Hi Richard, I have an article for TM for you." Yes, yes, this *is* the place.

*****

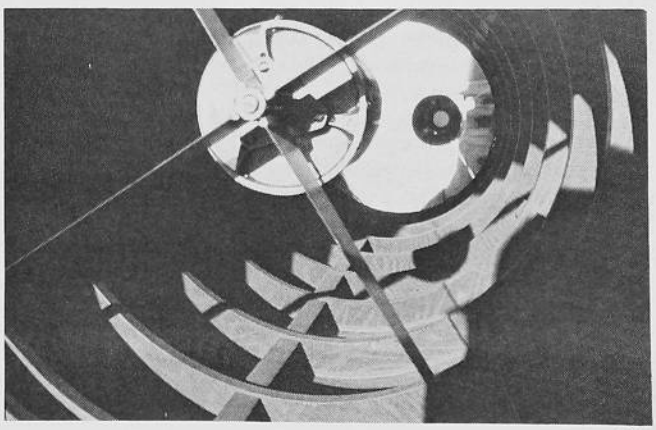
I've arrived on Wednesday, two days before RTMC, to attend the Big Bear IAPPP meeting. Years ago I did an M.Sc. thesis on photoelectric photometry, so the subject is no mystery to me. As interest in amateur astrophotography peaks out, as it seems to be doing, PEP, of all the developing areas of amateur astronomy, seems to me to hold most promise for the future. Why? It produces results of significance. It's becoming technically less complex. Good telescopes, good mounts, and commercial photometers are available. Computers are common enough, now, to crunch through the math that photometric data require. There are also enough astronomers willing to define problems that need photometry that the burden of finding meaningful projects is removed, or at least shared, with the professional community. All the elements are falling into place — including the IAPPP and AAVSO to coordinate activities.

In the meeting hall, a number of photoelectric items — a photometer head with an Apple computer hooked up to it, a Sinclair ZX81, a little box of filters, a stack of IAPPP tee shirts — were on display. I met tee-shirted Jeff Hopkins who, along with co-chairman Kenneth Kissell and local arrangements organizer Don Rohe, had put this meeting together. Jeff's wife was running the registration table, and I registered.

After settling into the dorm, taking a little nap, and eating the Camp Oakes supper, things got under way with an informal discussion. After introductions,

Bob Fried (pronounced freed) got up and began talking on the problems PEP people face. Although second order extinction coefficients seemed to dominate the discussion for a while, other problems also began to emerge. PEP is a new field, and there is only one source of information for the intelligent non-technical layman on the techniques of photometry and the handling of data once it's collected. (Note added at the last moment — this has changed; there are now two: *Astronomical Photometry*, by Arne Henden and Ronald Kaitchuck,

Dan Raether and Carl Blue crafted this beautiful 17.5" Dobsonian from ⅛" birch veneer plywood tube. The rocker box breaks down for portability and the tube rotates. Note internal bulkheads.



Walt Schoendorf of Alameda, CA, mounted his 17.5" mirror in an open tube. Each side panel is one piece of plywood — resulting in a solid truss structure. The rocker is unusually low and compact. Side bearings are hardware store "rounds" wrapped with an aluminum strip.

Van Nostrand Reinhold, $30, has just come out. It's great.) Many of the current generation of PEP people are still in the "hardware development" stage, as the *IAPPP Handbook* attests.

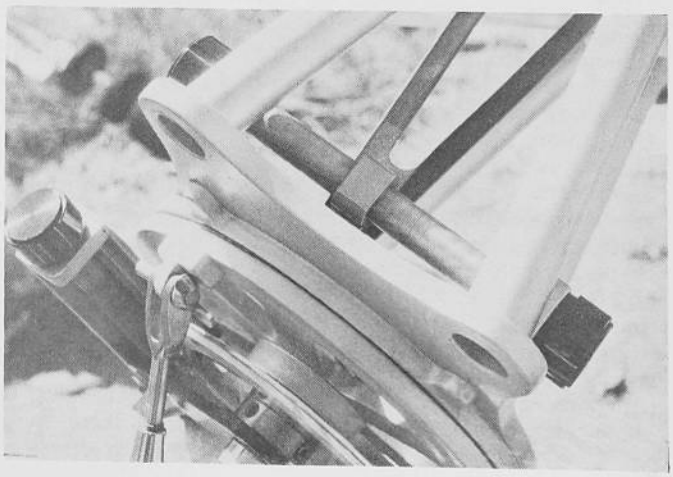
Still, in order to attract more people to this work, some group such as the IAPPP or AAVSO will have to write something like a series of "lab exercises" that a person might work through to become fully familiar with the vagaries of photometry.

You might start, for example, by spending an evening monitoring one star, either rising or setting, then plotting air-mass versus deflection in magnitudes to obtain the (hopefully) linear plot whose slope is the extinction coefficient. The next "lesson" might be to repeat the first experiment in several colors to determine k_B and k_V for the instrument, this time using an analytical method to determine slope — and so on, one logical step at a time. At the end, not only would you understand PEP, but you would have determined transformation coefficients for your photometer — and even the second order extinction coefficients.

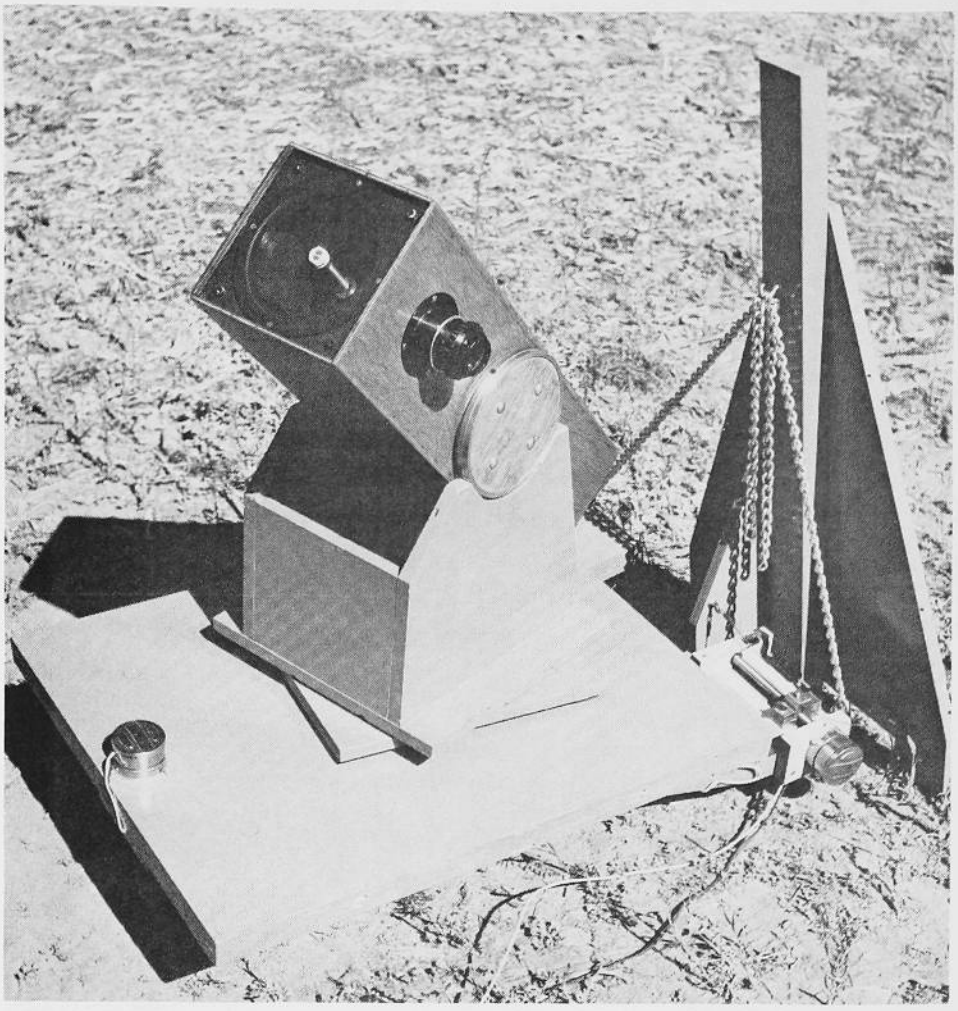
It also seems that this field needs a "black box" computer program, maybe in a common and fairly transportable language such as BASIC, that could prompt someone to enter the correct data off charts or out of a log book and then perform the reduction.

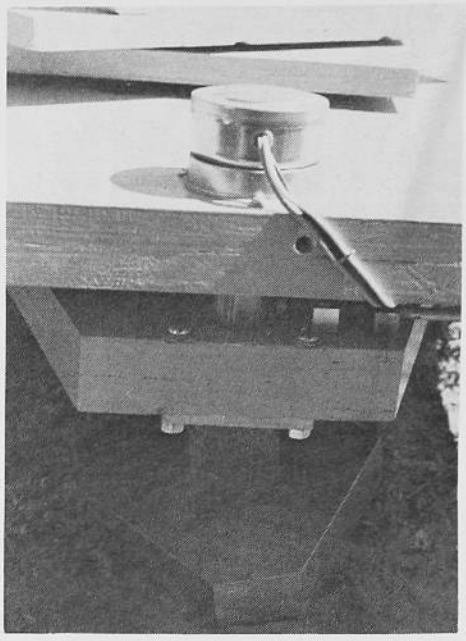
The next morning I woke at 6 a.m. to bright mountain sunshine pouring in the windows of the dorm. Breakfast, at 8:30, seemed a long way off. I went for a walk

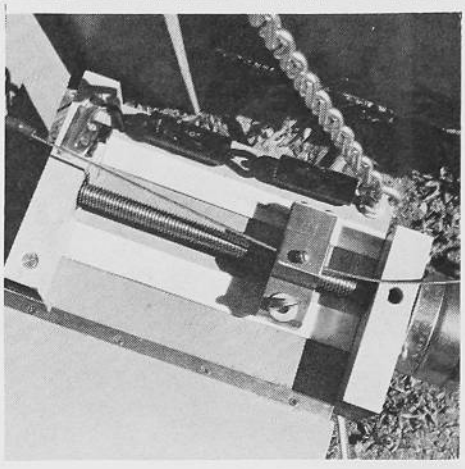
around the camp in the crisp mountain air. The camp was clean, very deserted, with little green shoots coming up all over the telescope field. After breakfast, the IAPPP symposium started. I won't discuss the papers here since they will be published as a special issue of the *IAPPP Communications*. Of interest to telescope builders are Bob Fried's paper on the Braeside Observatory, Russ Genet's on the Fairborn Observatory, Louis Boyd's paper, "Automated Telescope and Photometer" (which, under computer control, opens the roof, points at stars, takes data, closes down at dawn, and stores the results on a



David Piton's 6" f/15 sits on a solid mount with tubular fork arms. He uses a plastic protractor as a setting circle. Note tangent arm drives in both axes.







George Scotten built the "porch swing" mount and Jim Daley made the 6" f/4 Wright telescope. "It's something you can build without machine tools," said George. He balances it to swing, and the motor regulates the rate of fall. Note that both *RA and pseudo-declination axes are present.*

floppy disk).

For those interested in observing, Al Harris of JPL, Steve Edburg of International Halley Watch, and Jack Child and Robert Staehle of the World Space Foundation (which co-sponsored the meeting) discussed scientifically valuable observations of asteroids and comets that amateurs can make. They are actively looking for people to work with — if you want a program, they have it. By the way, anyone interested in the IAPPP should contact Robert Wolpert, Belmont Observatory, 144 Neptune Avenue, North Babylon, NY 11704. Order copies of the Proceedings from J. L. Hopkins, Hopkins Phoenix Observatory, 7812 W. Clayton Dr., Phoenix, AZ 85033.

Somewhat to my surprise, there were very few telescopes at the IAPPP — those who own telescopes tend to have big permanently-mounted ones — so we observed with a couple of C8s on Thursday night.

Friday morning was the session on specific observing programs. I gave a paper on a portable light pollution photometer and observations made with it in Ontario and Wisconsin. Around noon, the IAPPP meeting ended, so I drove down to Big Bear to look over the lake and get lunch. From the top of a nearby mountain, I could see across the lake and down into the cloudy valleys below, and realized that down in L.A. the weather was still terrible — but in the mountains, it was beautful, clear, and warm.

The Riverside TM Conference was well under way by the time I returned. There was a long line waiting at Registration. The little plants in the telescope field had been tramped flat and dust was blowing around — but telescopes of all sizes were set up. This was Riverside 82! Mike Sugarman suddenly appeared and asked me to talk to a reporter from a Riverside newspaper. Ben Mayer appeared and began talking about his TV series. Dennis di Cicco appeared looking a little tired from a two-week vacation before Riverside.

Telescopes continued to arrive until well after dark, with attendant headlights, dust, and moving vehicles. Since there were easily four or five telescopes in the 16"+ category, I commandeered one and started looking — but the image was mushy. I tried another telescope — same thing. The mountain breezes seemed to be extremely turbulent, and low stars flickered. I watched Scorpius rise, and waited for the Moon to set.

Once again, the Sun shone in at 6 a.m., and now, with the dorm full, it seemed wise to get up early while there was still hot water in the heater. I was third in line.

Saturday morning more people and telescopes arrived. The field had a rather circuslike quality, with various manufacturers and dealers spread around it. The homebuilt telescopes tended to be displaced toward the upper end or down among the trees to the east. The path leading up to the field was lined with sellers of tee shirts, buttons, astro-art, posters, drives, and Orion Telescope Center selling back issues of TM.

On the field, Coulter Optical had a prominent spot mid-field center, and it was filled with Zolatoned telescopes. When the 29" arrived, it looked rather comic. It's exactly like the smaller ones, but bigger — like Papa Bear, Mama Bear,

and two Baby Bears. Coulter is now selling all the Odyssey components individually, including mirrors.

Celestron had a table of discount parts, finders, and little what-nots in front and some C8s, C11s, and C14s equipped with solar filters. I had a glimpse of a new telescope product they will introduce soon — in an orange tube, of course. Just up the way, Meade seemed to be displaying their DS-10 and DS-16 more than the 2080. I didn't see their new 10" there. The DS-16, incidentally, is the first fast Newtonian I've seen used with a star diagonal. They seemed to be doing a vigorous over-the-counter business. A lot of money clearly changes hands at Riverside.

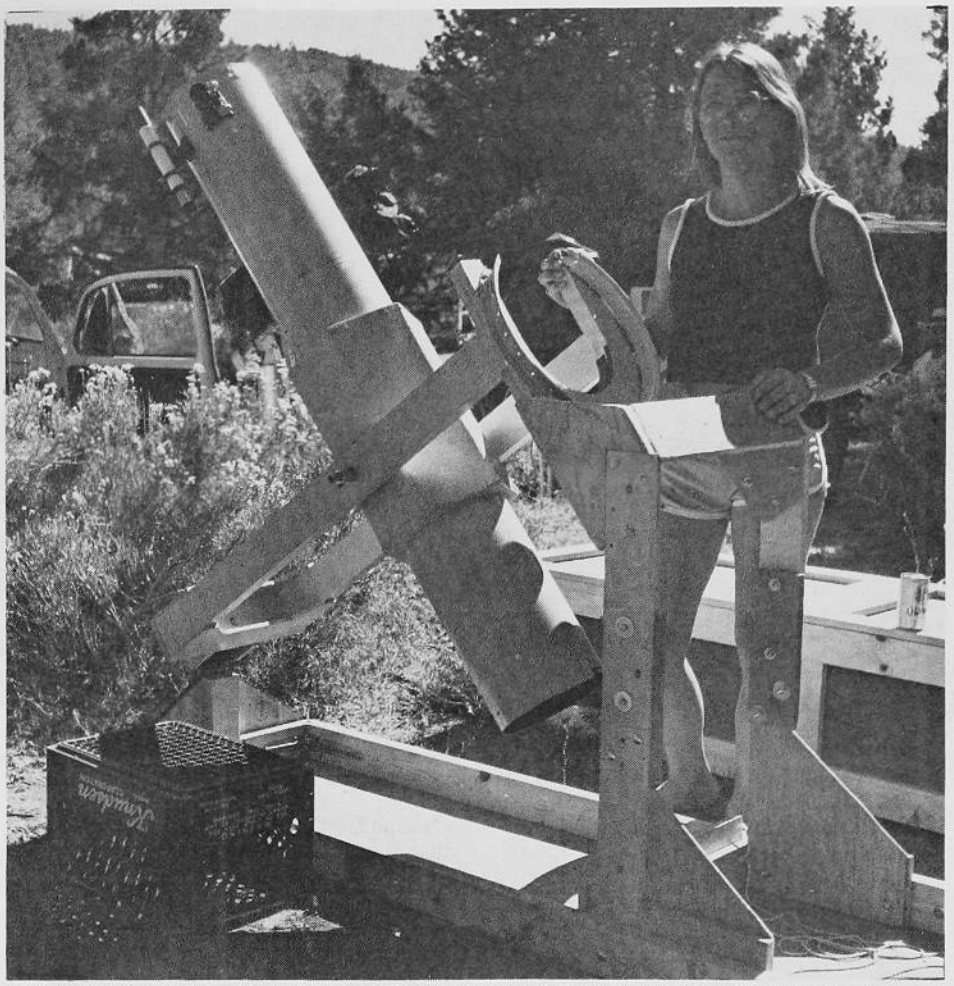
I spent the morning reconnoitering: poking under George Scotten's porch swing mount, the magnificent birch Dobsonian down Telescope Alley, Walt Schoendorf's plywood "Surrurier" tubed scope, Shaffer's collapsable, the handsome 20" f/5 from Fresno (its tube is made from 55 gallon drums welded end to end). In talking, Steve Coe mentioned that Thompson's Water Seal, a concrete sealant, is good stuff for sealing plywood — something I'll have to try.

This year seemed to bring out the refractors. There were several 6"-ers below the field, but they were terribly mounted, one on 4" ABS plastic pipe fittings and the other on a tall, wobbly column. Refractors are difficult to mount — they're long, and the pier needs to be tall to give ground clearance for the eyepiece. Next year I hope those instruments are back — but on better mounts.

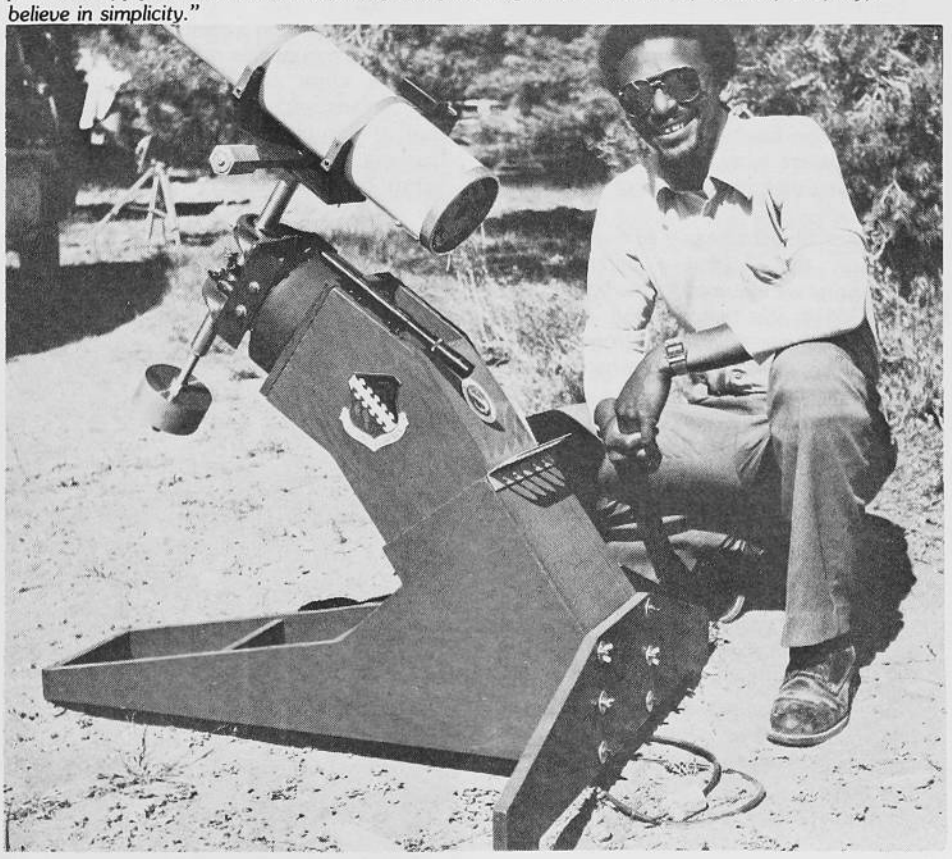
A big attraction, though I'm not sure to what degree it can count as an amateur job, was John Pons' 8.5" f/15.6 refractor. There is a lot to be learned from this instrument, however, since it is very solidly mounted. Pons spent much of the time I saw him fussing around the telescope, assembling and disassembling bits and unwrapping and wrapping it with plastic. The wind came up and it was getting covered with gritty dust — you had to see the beautiful gloss white and jet black finish to appreciate his concern.

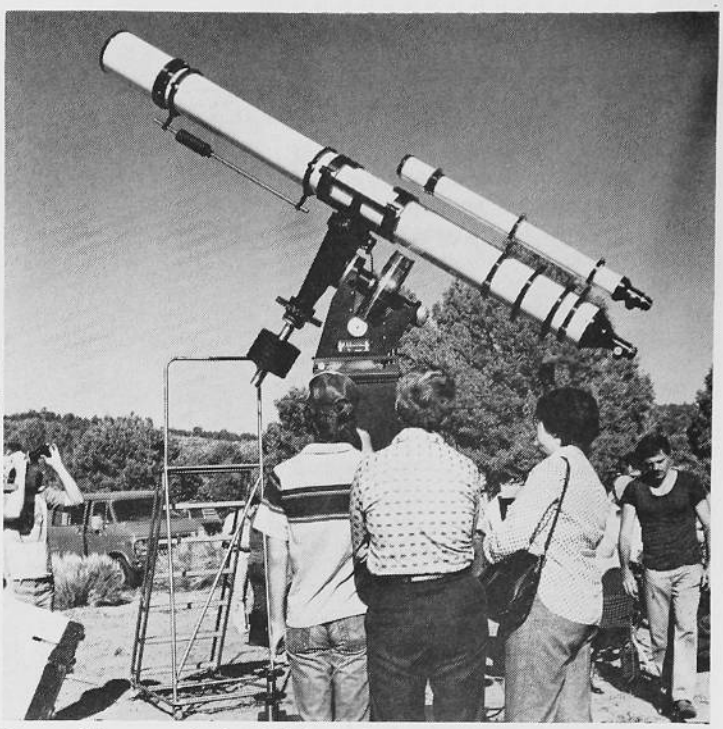
My paper was scheduled for 2:45, so I kept nervously glancing at my watch and finally showed up about 30 minutes early only to find that things were running behind schedule. I'd been scheduled for more time than I'd asked for, and I felt a little ill from being out in the Sun too long, so I gave it quickly — after all, any idea can be expressed in five minutes. The paper, which will be published in the *RTMC Proceedings*, is about the "polar plate" variation on the German mount. It can be built from simple materials, with a minimum of tools, and is more stable than the usual kind.

The paper over, and the schedule



Kristin Karalus of Riverside built a portable yoke mounted 8" f/8 Newtonian. The horseshoe is made from a bicycle rim. Keith Lawson of Palmdale has a portable and effective "astrographic" pier made of plywood. He uses the riflescope for polar alignment. "No circles," he said, "but, hey, I believe in simplicity."





Tom Scott and Terry Boone of Fresno made their 20" f/5.2 reflector for $600 out-of-pocket. The tube is 3¼ steel drums long. John Pons designed an 8½" f/15.6 refractor and Byers did most of the machine work.

substantially caught up, I relaxed to watch Rick Shaffer's demonstration of his collapsable 17" telescope that fits into a Honda Civic. This scope, which is pretty nifty, will be written up in a future issue of TM.

The Swap Meet was just getting started when I went back outside. My impression was that the number of real "goodies" was way down this year. Maybe the supply of surplus eyepieces had to run out someday. Anyway, I bought an 8" mirror for a reasonable price, so it wasn't a washout.

Saturday evening brought Door Prizes and the evening speaker, Dr. Eleanor Helin from JPL. She has been discovering Earth-crossing asteroids for some years now, and described the emerging picture we have of these little bodies.

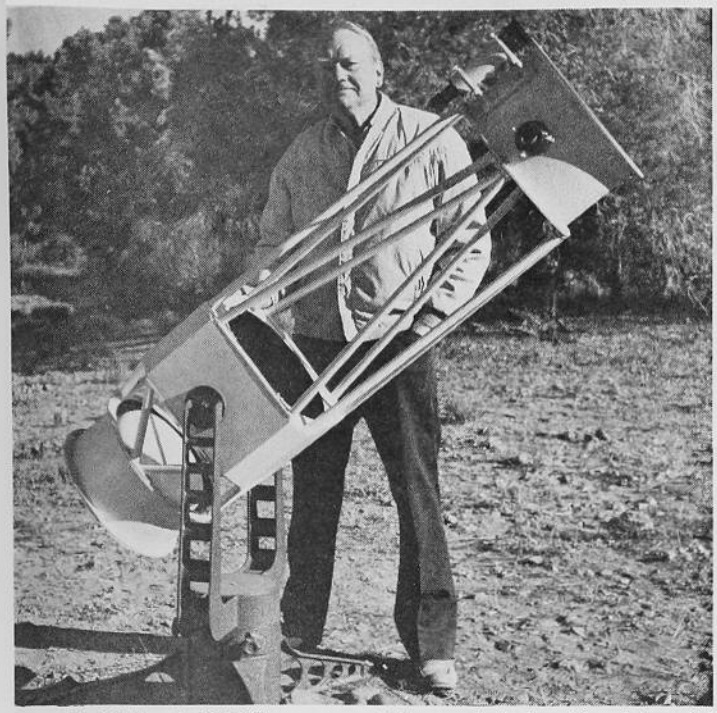
I met Shoichi Sezaki of the *Tenmon Guide*, the Japanese astronomical magazine we featured on the back cover of TM#14. We talked about American and Japanese amateur astronomy. He said, "In Japan many amateurs do nothing but take pictures, but in America, many watch [i.e., look through their telescopes] much more. I do not think this is so good. In Japan, they must watch more."

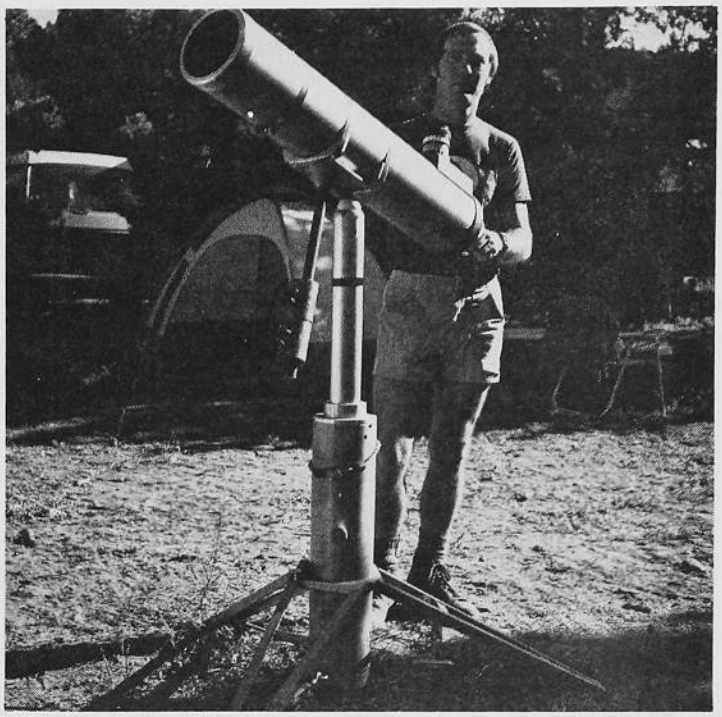
It was getting dark, but I felt rather pooped from the day so I went back to the dorm and lay down. After a few minutes, I felt energized again, and the prospect of clear skies and (hopefully) better seeing tempted me back toward the telescope field. I started walking up the hill, and spotted some friends in the dark, so we talked and waited through some long lines to get a peep through an eyepiece.

Then, since I really wanted a glimpse through Coulter's 29" prototype, I got in that line while the others wandered off. The night was beautiful but moonlit, bright enough that I tried handheld time exposures of the people ahead of me looking through the eyepiece of that behemoth. Finally, up the steps and there was M-13, rather soft at 135x. The seeing was 3 or 4 arc-seconds, so there really was no way to tell how it might have performed on a dark, clear, steady night. The mount was rather stiff, but M-13 was close to the zenith, where Dobsonians seldom do well. I could see Scotty Houston's triangular dark marking, though it seems to show up better in smaller telescopes.

I asked Jim Jacobson about the 29", and he said that the mirror in the telescope was not good. It had, he said, some zones at the edge that he hadn't had time to remove, and it needed several more days of figuring. I also put my hand on the tube and the tube box in several places, and noticed that the tube was still warm from the day's sunshine. Like my own 20", letting sunlight fall on a telescope of this size probably guarantees bad tube currents until midnight. It's been my impression that big Dobsonians could profit from air conditioning. For the price, once they get the bugs out, this will be a fantastic telescope for a club.

Gerry Logan and Gene Lucas talk about the fine points of Logan's 8" f/6 Jones-Bird reflector.





Dick Nelson's 12.5" f/5 snap-apart telescope is designed for air travel. The fasters release with a quarter-turn. Jack Child's 6" f/5 RFT refractor gives fantastic *views of the Milky Way. It turns on an omnitorial mount.*

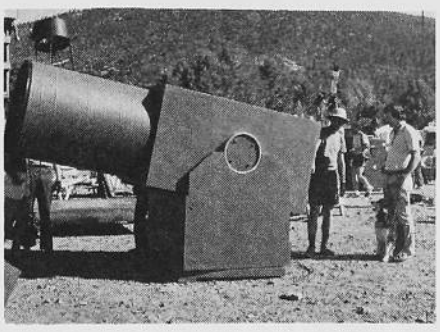
Sunday morning came too early. At 6 a.m. the Sun shone in my face and I woke up. I grabbed an early shower, then read over the notes I'd made Saturday. After breakfast, I was scheduled for a "workshop" on telescope mountings in the fire ring near the swimming pool. The group there was very good, and we got a discussion going with lots of fine ideas. But mounts are a topic that seems to polarize people. What I think must be understood is this: the way you will use the telescope determines the appropriate type of mounting for it. Obvious? Maybe not. For visual observing and portability, a Dobsonian is fine. For photography with portability, a fork is okay. For photography and any task demanding excellent tracking, yokes, horseshoes, and English mounts are best.

After the workshop, it was lunchtime. Bob Kestner and I spent a while discussing his article on figuring, and then I hung around to see the Digistar presentation — a high resolution (4096x4096 pixels), high intensity CRT driven by a PDP-11/34. It can project a planetarium sky, or move through the stars within 200 light-years. It's utterly weird to fly at 100c toward Betelgeuse.

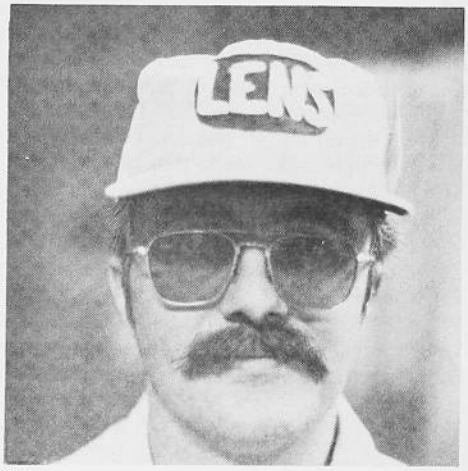
In the afternoon, I looked at David Pitou's 6" Maksutov and Gerry Logan's beautifully done 8" f/6 Jones-Bird telescope — as stubby as an f/3.5 would normally be. Then I kept a promise I'd made and over in the trees, described everything I could remember about a TLP I'd seen 20 years earlier while a bright-eyed young woman from the World Space Foundation took notes. They are researching TLPs. This particular TLP is interesting since I was working at Yale's Bethany Observatory as an observer on a 20" telescope equipped with a powerful H-alpha spectrophotometer, and we may have gotten observations of it.

After dinner, it was tjme for speeches, awards, door prizes, and more speeches. Ashley McDermott opened the proceedings with a message to "leave the grounds cleaner than you found them," then turned it over to Cliff Holmes. Cliff thanked "all you fellows and girls who helped out, and all of you who came — we've had a good time." Mike Simmons said that Riverside is, he thinks, the biggest and the best conference, and thanked George Scotten (from Stellafane) and "the yodelling Twinky peddler" (Cliff) for putting them on for us. George commented that "one star party is like any other," but added, *vis-a-vis* Stellafane, that "half the scopes out there are bigger than our whole collection."

Doug Berger got three cheers for his winning the Bruce Blair Award of the WAA, then Ben Mayer was called for his ASP Amateur Achievement Award. While his grandson Shawn gurgled, Ben said, "It is time we create a groundswell against the Proxmires" by publicizing astronomy; that we must be "a little less proud of what we know and a little more sympathetic to those embarrassed by how little they know . . . let's not make it



Upper left: John Pons adjusts a counter weight on his refractor. Note the massive mount. Lower left: Rick Shaffer discusses the portable 17.5" he built. It folds down for transport in a Civic. Above: Making a mockery of scale, the 29" prototype drew much comment.



George Balazs crafted his 10" f/5.5 Newtonian one arm fork from light pieces welded together. The drive electronics are built into the pier. Left: Q: What is this man wearing? A: A "lens" cap!

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seem so difficult; let's let them know that anyone can share this love of the stars . . ."

Then came the awards. Pat Michaud said "this year was the hardest ever" to decide on awards, and not every telescope could receive one. To those who didn't get one, he said "don't take it too bad — and thanks for bringing your telescope for us to see." I was pleased to have called most of them myself. They are listed in a box in this article.

When Astronomy for America gave the Clifford Holmes Award to Dennis di Cicco, "one of the most avid supporters of amateur astronomy," Dennis was readying his camera to photograph the winner. "I'm very much embarrassed over all this," said Dennis, his face red; "it's my job to promote amateur astronomy, yet I'm one of you, too." Cliff

said, "He does it and he does it well — and that's what this is all about." Amen.

"What's next folks?" said Cliff.

"THE DRAWINGS!" said a thousand people.

By now I was holding nine tickets for people who had had to leave early, so each number called meant a scan down the stack — but none of the tickets I had won anything.

After the awards, and after copying a list of all the winners for TM, I walked up to the telescopes again. There was a brighter Moon, fewer people, but plenty of aperture still on the field. The seeing seemed to be better, too, but not good, as I looked through Tom Scott and Terry Boone's 20″ Newtonian and then through the Melland/Chandler 24″ (there will be an article in a future TM on this one, too) trailer-mounted telescope. I couldn't see the central star in the Ring Nebula with either one of them, and the images seemed a bit soft, so I must admit feeling a little pleased that California's skies can't always beat a good night in Wisconsin.

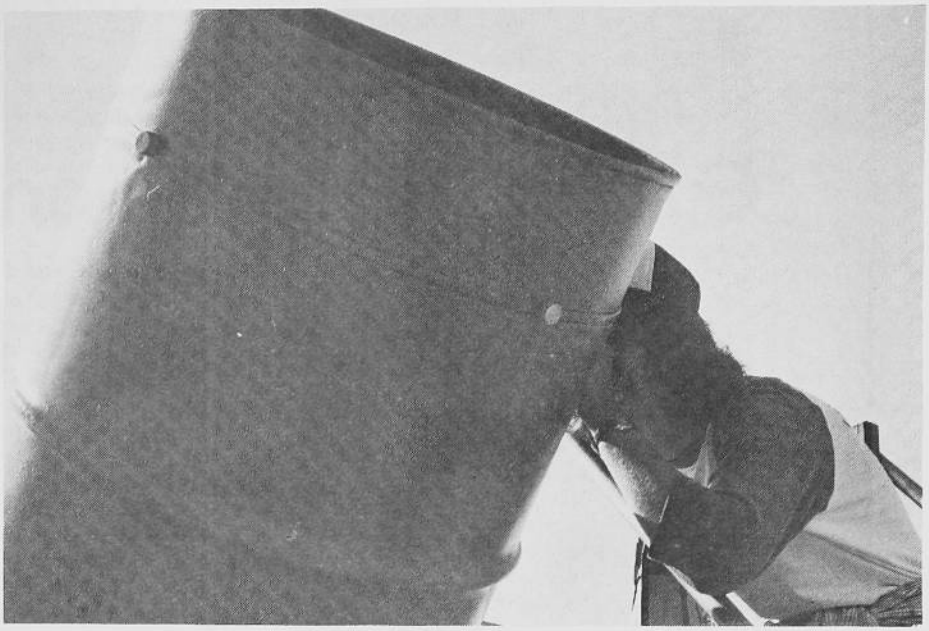
The best images I saw all night were with Art Leonard's 6″ Yolo TCT. Sometime I'd like to see it in operation without that darned apodizing screen and the multicolored blobs it makes all around Saturn.

Pete Manly had attached a portable TV camera to his scope and image intensifier (there is an upcoming article on Manly's CID camera in a future TM), so we saw the Ring and M-13 on a little color TV monitor. Afterwards, I strolled down Telescope Alley to the birch Dobsonian built by Carl Blue and Don Raether, thumped its sides and tested its "push," then found a few familiar sky objects. It's a fine machine.

Moonlight made walking and gawking easy. I looked through a 20″ Ritchey-Chretien (almost entirely commercial, optics by Star, mount by Shaeffer, quite steady), then on to Tim Parker's 8″ Springfield which I had reported on last year. The smaller telescopes were giving pretty fair images, so we looked at Jupiter, Saturn, Mars, and Uranus with it. Tim has plans to modify this telescope, but I certainly like it the way it is.

Although it was unattended, I wanted to look through Jack Child's 6″ f/5 RFT refractor on the ball (Omnitorial) mounting, so I took its paper bag lens covers off and swept it along the Milky Way in Cygnus, Cepheus, and Cassiopeia. What a gem this telescope is! With its big Erfle, the field is brilliant with zillions of tiny star images. I'd like one of these. The ball mount had a little bit of stick-slip chatter in it, but not enough to be annoying.

Finally, I don't know when it was, maybe 2 a.m., I got cold, gave up, and went to bed.



What happened at Riverside this year? There wasn't much new this year, and there wasn't much innovation; it was a year of consolidation. There was aperture, more than ever, as those 17″ telescopes come on-line. There seems to be a bit of a resurgence in refractors. But commercial forces are changing the face of this hobby, the new products obsoleting old skills. "Nobody here made his own mirror," said George Scotten, appalled. I would agree, except that I'm not sure I wouldn't rather see someone observing with an "impure" telescope than "still working" on a purist's telescope. On the other hand, and perhaps where George is coming from, if people never learn to make a simple 8″ paraboloid, they'll later lack the experience to make a big mirror, an R-C Cassegrain, the optics of a TCT, or a refractor objective. I'd certainly hate to see us trapped outside our own hobby by lack of the basic skills, and the hobby thereby impoverished.

Nonetheless, the reason we build telescopes is to observe — and Riverside is one of the biggest star parties in the world. In a hobby like astronomy, popularity brings commercialization, which also brings more people to the hobby. A meeting like Stellafane avoids the commercial altogether, but then there is the force of tradition and relatively few east-coast telescope influences to exert countervailing pressures on the organizing committee.

Nor do I think we're going to forget how to make mirrors. With a few people like Bob Kestner around, maybe some of us, at any rate, will become more ambitious than anybody dreamed we'd be a decade ago.

Or perhaps it's all a phase. Give it another five years, and nobody will want to be seen dead with an orange cat, blue cat, or white newt. People already apologize for using them. Fashions dictate change — deep-sky Newtonians might be OUT then, and refractors for planetary observing IN. Maybe "1/20-wave" will be the rallying cry. Astrophotography already seems to be on the way out after a decade of fashionability, though I don't pretend to understand why.

Still, for me a meeting like Riverside doesn't end on Monday morning when I drive down the mountain, catch a plane, and fly back to Milwaukee. It continues as I write an article like this one, review the notes I took, look at my pictures, talk to other people about their impressions, compare what's happening at Riverside, Stellafane, AstroFest, or the Texas Star Party, and read the articles that arrive for publication in TM.

— *Richard Berry*

Grinding, Polishing and Figuring Thin Telescope Mirrors

Part 3 – Figuring

The key to figuring any telescope mirror is determining, on the basis of optical tests, what the figure of the mirror is before you begin the next figuring session. You can then work toward the surface you want, usually a paraboloid, by appropriate corrective polishing.

There are many ways of determining what you have and understanding what you must do to figure a telescope mirror. The more familiar you are with the subject, the easier it will be for you to formulate solutions to problems you will encounter in figuring a mirror. Figuring should consist of an equal mix of testing, thinking carefully before you act, and polishing.

You will find figuring a large mirror a bit simpler than you might have imagined it could be *if you have had adequate experience using optical tests before* and if you start with a smooth, nearly spherical mirror. The whole process may simply consist of a series of tests and general correcting strokes with no trouble with zones. For those who aren't so lucky, your strategy should be to take care of your worst problems first. Work toward a smoothly undercorrected curve before continuing with the correcting strokes, fixing any irregularities as they occur.

Goals in Figuring

When should you pronounce a mirror done? I'd suggest that you figure it until you cannot detect any significant problems in the figure. The reason for this is that for all but the most experienced telescope makers, the problems you'll see in the figure will turn out to be worse than you thought they were once the mirror is aluminized and put into operation. It is best to eliminate all the errors you can detect even though a calculation may show a certain error will not be too severe. Besides, it may save you years of saying, "One of these days I am going to refigure this thing."

On the other hand, I guess I should say something about how good your mirror has to be — or rather how bad it can be — and still function,. but all my experience tells me that there is no quantitative answer to this question. Certainly I'm not going to be caught saying something like "a ¼-wave mirror is good enough," or "a ¼-wave mirror is not good enough," when there are so many unknowns.

The largest unknown is whether a mirror alleged to be ¼-wave really is as good, or as bad, as its maker reports it to be. In general terms, it is almost impossible for any amateur to determine the true wavefront error of a mirror. It isn't that amateurs are in any way inadequate, it's just that true wavefront analysis requires sophisticated interferometric test equipment that very few people have access to.

I look at it this way: Monday through Friday, as a professional optician, my optical work is done on information accurate to a very small fraction of a wavelength of light. On the weekends, as an amateur astronomer and telescope maker, I rate telescopes as being in one of five categories: excellent, very good, good, poor, and unusable, using the star test.

I have tested hundreds of telescopes this way, and, with a certain amount of objectivity, I believe I have acquired an adequate method of judging telescopes.

An excellent mirror is one seeming to have no significant focus error at all. This represents a very small percentage of the telescopes I have tested — whether amateur-made or commercial.

Very good is given to telescopes that display a small amount of focus error, but that error has little or no practical effect on the resolution. Maybe 10% of active telescopes can claim this.

Good is given to a telescope if the focus error is judged to limit the telescope only at high power. Most amateurs have a mirror that warrants this rating — and most of them never acquire the expertise necessary to feel limited by the problem. Not all, but most. I might add that most of the discontent I've seen among amateur astronomers regarding the image quality of their telescope stems from poor alignment and/or turbulence mistaken for bad optics.

A poor rating is given to telescopes judged to be limited above low power. Telescopes of this caliber are extremely useful for deep-sky observing where the power can be held to less than 15 power per inch of aperture. For planetary observing and splitting double stars, the limitations are obvious.

Unusable is a rating you don't see much. It is usually the result of a bad mistake. A couple of cases come to mind — one of the worst was a 10-inch f/5 mirror sold by a now-defunct commercial supplier, accidentally shipped with a spherical mirror. Another was a homemade Cassegrain with a badly under-corrected secondary.

The point to all this is that you should make your mirror just as good as you can. It might make me look good to say, "nothing less than an excellent rated mirror

should be tolerated," but that would be both pompous and ridiculous. Only the most experienced opticians can hope to make such a mirror. The way you gain experience is by doing it, and you'll never do it if you get discouraged by a promise that only a perfect mirror will do. Mirror making is learned by doing — there is no other way.

But even the most inexperienced telescope maker who has grasped the concepts and has the skill to polish glass can figure a 16" mirror that will rank in the poor to good class with nothing more than a 150 line Ronchi screen used at the focus of his telescope on a star. This will give him a working telescope, albeit one with certain limitations, and the experience needed to do a better job the next time.

However, it is my hope that the majority of mirror makers reading these words have had the experience to apply the ideas presented in this article to obtain a well-figured mirror with no practical limitations.

Test Methods

Several test methods exist for testing parabolic telescope primaries. Each test has its strong points and weak points. In general, it is best to use several methods of testing so that you can cross-check figure errors.

The auto-collimation test employs an optical flat the same size or larger than the mirror to return light collimated by the mirror back to the mirror again. This test offers many good points, one of the strongest being that it is a null test, but it is difficult for ATMs to obtain use of an acceptable flat, so I will not dwell on this test.

The Foucault test has the opposite problem: it is not difficult to make a Foucault tester rig. Virtually all books on telescope making have detailed instructions on how to build one and how to apply the test. The problem is that the Foucault test is not a null test for a paraboloid — so a paraboloid is seen as a mistake in the optical figure of a sphere. You are left to measure the errors in the sphere and then calculate the curve they represent. Fortunately for most of us, this is not an unsurmountable problem. If the zonal measurements are made carefully and instructions are followed closely, you can make excellent mirrors with the Foucault test.

The star test uses only the telescope itself and a bright star. This test has the advantage that it is a null test for a paraboloid. If you know how to apply this test and have a night with good seeing, you can immediately evaluate a telescope mirror. Of course, it is not without its problems — the biggest that you are at the mercy of air turbulence while testing. Air turbulence can make the test difficult to evaluate, blurring or covering up problems in the figure of the mirror. Clouds and daylight have their obvious effect. Despite all this, it is not a bad way to figure a mirror. I have done some of my best work using it.

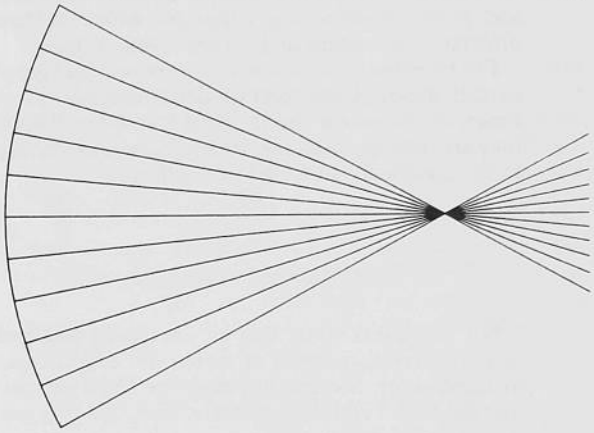
My personal favorite test for figuring telescope mirrors is the Dall null test. The Dall null test is similar to the Foucault test except that a plano-convex lens made from optical crown glass is placed in front of a pinhole or slit. The light returning from the mirror is cut with a knife edge — just as when testing with the regular Foucault test. The lens, called an aspheric compensator, introduces aberrations into the outgoing light that cancel the errors a paraboloid would normally display at the center of curvature. If applied correctly, a good lens and test rig can compensate the paraboloid's aberrations to better than 1/20-wave. The problem with this test is making the lens. Not all telescope makers are cut out for lens making, and the lens has to be a good one or the mirror will inherit its flaws. Furthermore, the spacing between the pinhole and the lens must be set within a couple thousandths of an inch which requires access to a large set of micrometers or an accurate caliper.

The wire test cuts the returning light at the center of curvature with a wire. I have never used the wire test, but from what I have read, it appears to be a manageable test. A description of the test can be found in TM#6.

There are many other tests available, most of them more sophisticated versions of the Foucault test. These tests all too often rely on the skill of the person doing the test, a skill which must be acquired by doing it.

The Sphere at C of C

A spherical figure is a section of a sphere. Its prime characteristic, from our point of view, is that it focuses all light emitted from the center of the sphere, or center of curvature, directly back to the center of curvature with no deviation at all. When tested by the Foucault test, the knife edge cuts all rays and the mirror appears to darken evenly. The Foucault test is a null-test for the sphere, because you see no deviations from a uniform darkening.



You must learn to picture the mirror's curve in your mind on the basis of indirect evidence about its shape and to choose the right focus for the curve based on what will be easiest to fix with a polisher.

At the center of curvature of a spherical mirror, all the light returns to this point evenly. Since the surface of the mirror under this condition appears even-lit, or what we call "nulled," the shape of a spherical mirror tested at its center of curvature can be expressed as flat or with a straight line.

The very same surface can be expressed as concave or convex if we just think about it focusing too long or too short. You must be careful here so as not to get confused by the telescope maker's jargon — what we mean is "relatively convex" and "relatively concave." If we test a concave sphere with a radius of curvature of 50" at a distance of 49.75" from the mirror, or 0.25" inside the actual point of focus, we can think of the mirror as having too long a focus, or being convex, relative to a sphere of 49.75" radius.

Even though you know the mirror is concave, with

respect to this shorter focus "reference sphere," the 50" radius mirror is convex.

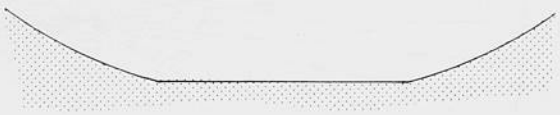
On the other hand, if the same 50" radius mirror were tested at a point 50.25" from the mirror, or 0.25" outside focus, you would find it concave relative to the 50.25" radius reference sphere. Of course, it is a deeper mirror, and really is more concave. Opticians express its shape as concave.

Remember, this same mirror, when thought of or tested at its focus, is expressed as flat.

For an optician who is making a sphere to an exact radius, this is important. Even though he may have a 1/20-wave concave sphere, if the radius of the sphere is too long, it must be thought of as being too convex.

But for the amateur telescope maker, small errors in the radius or focal length of the mirror are not important. This freedom to change the radius, both conceptually and really, is extremely important when we have a problem in the figure and we are trying to fix it.

For example, let's take a mirror we wish to figure to a perfect sphere. Under test we determine that the outer zones of the mirror are focusing too short. Therefore they are high, so we express this as concave with respect to the spherical curve we want as flat.

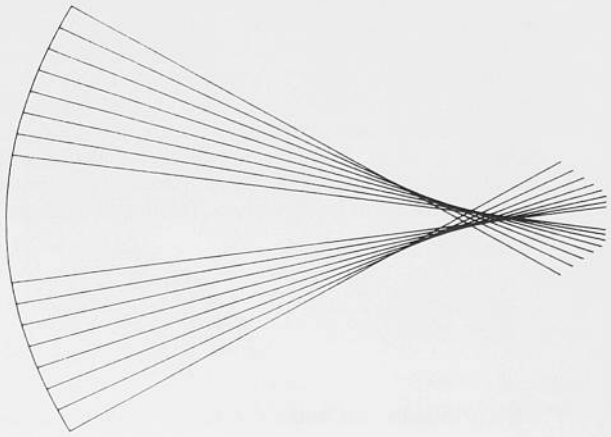


But this same curve can be expressed and treated quite differently. Instead of saying the edge zones are focusing short, and are therefore too high, we can say that the center zones are focusing long, and they are too high or too convex.

This is the same mirror, but we've changed how we think about it and what radius we want as our reference. However, it is much easier from a glassworker's point of view to reduce the center than it is to reduce the entire edge. From this perspective, the time spent thinking is worthwhile and could save a lot of polishing time.

The Sphere and the Paraboloid

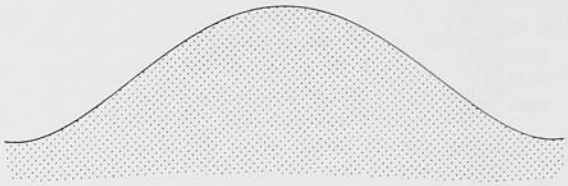
Now let's consider a spherical mirror focusing parallel light from a star. No matter how you focus, a spherical mirror will not bring together light to a single point. The effect is called spherical aberration. Note that the central regions of the mirror have the longest focus.



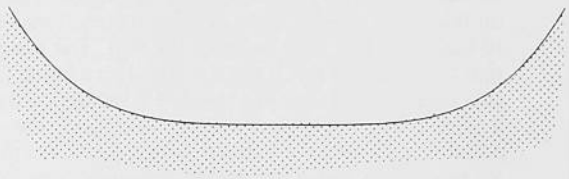
Testing a sphere with parallel light is not a null test. But parallel light is, of course, a null test for a paraboloid — our desired curve for a Newtonian telescope. A sphere is not represented by a straight line when we use a test that nulls for a paraboloid, but a perfect paraboloid is.

So, how will the sphere look when a paraboloid is thought of as a straight line? At a focus chosen midway between center and edge, with respect to a paraboloid, a sphere has a high center and a high edge.

Focusing near the edge of the sphere, or a shorter focus, the sphere departs from a paraboloid by having a progressively higher center.



Focusing near the center of the sphere, or a longer focus, the sphere departs from a paraboloid by having a progressively higher edge.



Starting from a sphere, you can see there are three basic ways to parabolize a spherical mirror. First, you can reduce both the center and the edge keeping the focus the same; second, you can reduce the center shortening the final focus; and third, you can reduce the edge lengthening the final focus.

Smaller mirrors are usually parabolized by the first method. Large mirrors, especially those with a large departure from a sphere, are parabolized using emphasis on the second method.

Now let's return to the center of curvature test where a sphere gives a null. Relative to a sphere, a paraboloid gives the classical "doughnut" curve when focused for a reference sphere chosen to null the paraboloid 0.7071 of the way between its center and edge.

It is possible to treat this topic in a much more mathematical way. A discussion of the curves using conic sections or as functions in x, y and z axes can help you understand mathematically what's going on. But from a practical point of view, this information is already covered in most books on mirror making. If you're still fuzzy, I suggest you consult them.

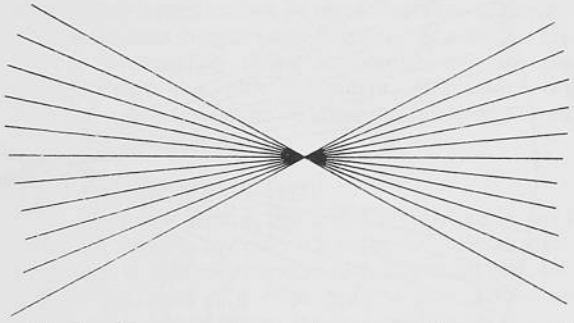
Star Testing

Star testing is a null test. When the optics are right, the image is right. But its limitations are obvious — you usually must test at night. However, many early figuring steps can be done during the daytime using the glint of sunlight reflected from shiny powerpole insulators or a glass tree ornament hung several hundred yards away.

The biggest problem is turbulence. Air currents stir up the star image and make testing very difficult at times. This is more disturbing to someone figuring a telescope mirror than someone evaluating telescopes for practice at a star party. When you're figuring, you're usually working from your driveway on any given night, but when you're examining telescopes, you're probably at a star party at a site that has been chosen for its good seeing. You don't need perfect seeing to star test, but you must avoid really bad seeing.

In following this section, you must make good use of your imagination. The computer generated ray-trace figures give only a rough idea of the appearance of the star image. Compare these to the plot of spherical aberration ray errors. Notice especially how the light rays bunch together at various planes of focus to cause a bright ring or central spot.

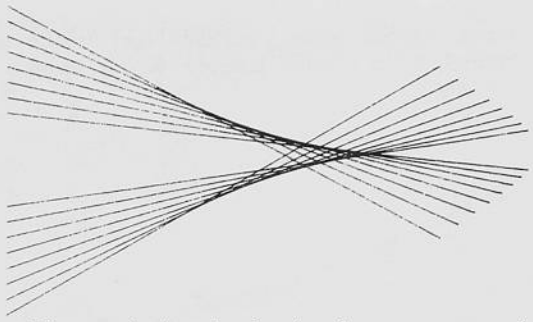
The star test as it is applied for our purpose uses the out-of-focus image of a star formed by the mirror. Although there is plenty of information in the focused image, the most useful information about the overall figure show up inside and outside focus. The reason is that the aberrations have longer or shorter focal lengths that cause light from a zone to concentrate, or reach its focus, inside or outside the main focus. What you'll be looking for with the star test, then, is the distribution of the light in the expanded near-focus disk of a star.



Ideally, for a perfect telescope with a central obstruction, the inside-focus and outside-focus disks look exactly the same. Both disks appear as round and evenly illuminated sets of diffraction rings with a dark region in the center due to the secondary obstruction. The outermost ring of the star image and the first ring around the diagonal hole in the center will be brighter due to the diffraction. These diffraction effects can be separated from the figuring defects you're looking for because the diffraction effects are the same on both sides of focus.

As you run from inside to outside focus with a less than perfect mirror, you can spot these differences, from not enough light in a zone to too much light, pretty easily. Light from a particular zone may bunch up on one side of focus and disperse unevenly on the other side of focus.

In order to make a proper diagnosis of the figure problems in the mirror, you have to understand how the rays from various zones behave as they go through focus. Then, when you actually observe the effects of the zones, you'll be able to estimate where the zone is and whether its radius is too long or too short.



When you look at the drawing above, you can see how the rays of light bunch inside focus due to the short focus of the edge. Where those edge rays intersect, the light is more concentrated, and you would see brighter rings. Outside focus, the edge rays are spread out and you would see a dim area in the star disk.

Doing a Star Test

Now let's get down to actual testing. The first step is to collimate the telescope correctly. For an unaluminized mirror, only the brighter stars in the night sky will do. Don't worry, a first magnitude star will be plenty bright enough. Even with no aluminum on a mirror, glass reflects about 4%, so your mirror will form an image as bright as a fully reflecting mirror of 20% the aperture. With an aluminized mirror, bright stars can be too bright for effective testing, and you'll want one of the less famous stars to test on.

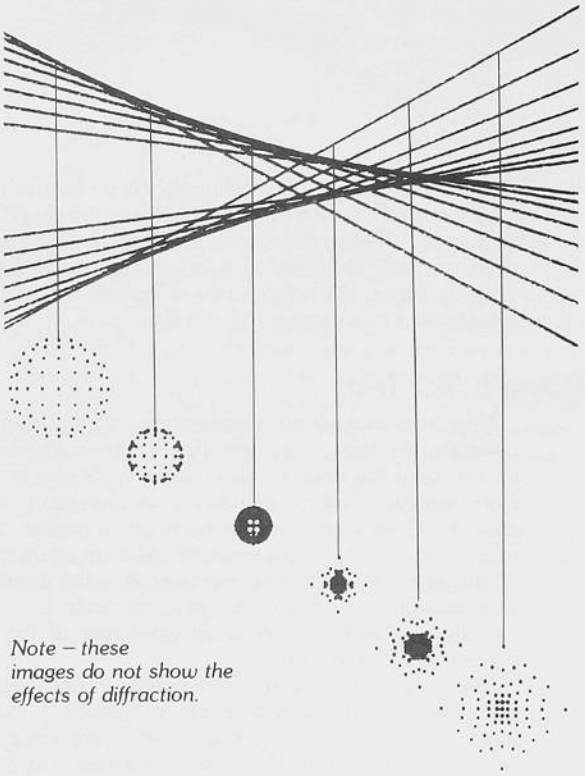
The magnification you use depends on how bad the mirror is and limiting factors like turbulence. I find the most useful magnifications lie between 6x and 25x power per inch of aperture. When you first test just at the beginning of polishing or during the early stages of figuring, errors in the correction of the mirror can be detected with as little as 6x per inch of aperture. As the figure nears perfection, powers of 15x per inch and above become useful. Magnification above 25x per inch can lead to diminishing returns especially on large mirrors where turbulence is likely to be a problem — and what you have to see can be seen at 25x per inch of aperture anyway.

At low magnification, that is less than 10x per inch of aperture, or with eyepieces longer than 25mm focus, spherical aberration in your eye or eyepiece may appear as errors in the mirror. Above 10x per inch, this effect becomes negligible. It has been my experience that Kellner, Orthoscopic, or Plossl eyepieces, except those over 25mm focal length, do not introduce aberrations that affect the distribution of light in the star disk.

Your eyes may be a problem if you have extremely bad vision. Nearsightedness and farsightedness don't matter, and most other problems that may be present in the eye are taken care of by using a small exit pupil. However, astigmatism may remain a problem even with small exit pupils. You can usually take care of this by wearing your glasses that correct the astigmatism. You can tell if any astigmatism you see is in your eyes by checking whether it rotates when you rotate your head.

Let's start with basic undercorrection, or spherical aberration as it is called. Remember, an undercorrected parabola has a short-focus edge and a long-focus center. Starting well inside focus and racking the eyepiece outward toward focus, you'll see the edge of the out-of-focus disk get brighter and bolder while the center starts losing light. Starting from outside focus and moving inward toward focus, you'll see the center fill with light and the edge become dim and poorly defined. Very near

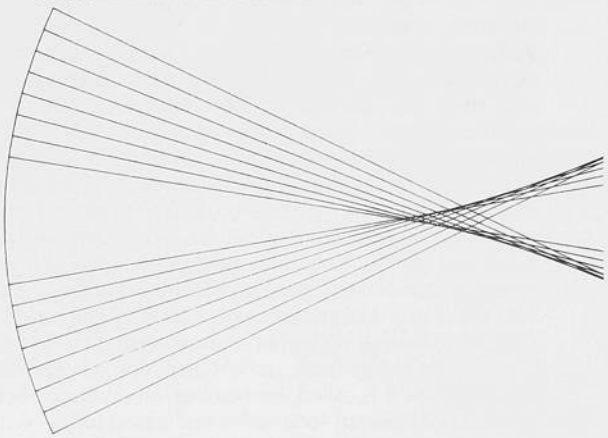
focus or just outside it, the dark spot caused by the central obstruction will disappear entirely as the center focuses.



Note – these images do not show the effects of diffraction.

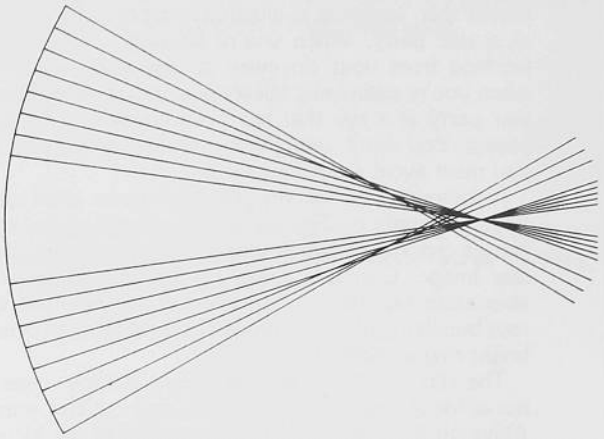
The computer drawn ray-trace images show how a light from a 16" f/5 mirror corrected to 90% of a full paraboloid focuses over a range plus and minus 0.4 millimeters around the best focus. The degree of correction is, of course, proportional to how pronounced these effects are in the test.

An overcorrected mirror, one with a short focus center and a long focus edge, will display just the opposite patterns. Near focus on the outside, energy builds up at the edge, and on the inside of focus, energy concentrates in the center.

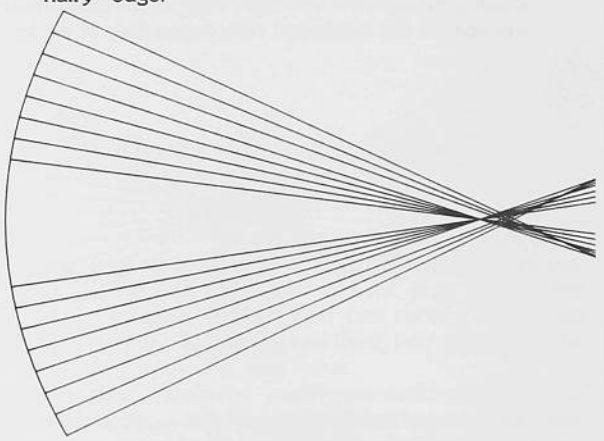


Over or under-correction is easy to interpret. Even when it is very slight, it can be seen very near focus at high power. Note that temperature changes on your mirror will show up as correction errors, either under or over depending on the direction of temperature change. Interpreting these correction errors must be done carefully, especially if the mirror is plate glass.

What's involved if the error is not a smooth correction error? Suppose you have a parabolic mirror with a raised, or short focus, edge. If the only thing wrong is the short edge, and the rest of the mirror is paraboloidal, you'll see an effect at the edge that looks a lot like undercorrection. If you watch the behavior of the center, though, you'll see that it focuses properly, which gives away that the problem is just a raised edge and the rest of the surface is okay.



A rolled edge or turned edge has a very distinct effect on the star image. The edge has a bad slope error so it will rapidly defocus. The outermost ring will be bright outside focus, but the effect inside focus is dramatic. Around the edge, the disk just wastes away. It has also been called a "hairy" edge.



If the turned edge is on an undercorrected mirror, inside focus the usual bright outer ring will have a blur of diffuse light surrounding it. Outside focus, where the extreme edge would be weak due to the undercorrection of the mirror, the star disk will have a thin, bright outer ring.

Zones on the mirror show up as bright rings in corresponding parts of the defocused disk on one side of focus and as darker areas on the other side of focus. Where a zone has a shorter focus, the bright ring will be inside focus. Long focus zones show a brighter ring outside focus.

Don't be discouraged if this is hard to visualize — if you remember the basics and understand how the test works, you'll recognize these things when you actually see them.

A drawback of this test is that it is not always apparent how wide the bad zone is. The solution is to place tape on the mirror or use stop-down rings. Several stop-down rings of different inside diameters will allow you to

change the aperture of the mirror to isolate the zone. The procedure here is obvious.

A useful addition to a star test is a 150 line Ronchi screen. This allows you to see the boundaries of the zones as bumps or wiggles in the Ronchi bands. Used with stop-down rings or tape on the mirror, this Ronchi null test is helpful in marking zone boundaries.

The Ronchi screen is also a valuable test for overall correction and smoothness of figure. I recommend that you use it in conjunction with star testing as a check and backup for your interpretations.

Turbulence affects the star test by stirring up the diffraction rings near focus. Bad turbulence usually gives the impression that the mirror is better than it really is since no zones or change inside or outside of focus will be noticed. An experienced star tester can tell when this is happening, but it can fool almost anybody, so watch out for it.

Turbulence inside the tube can settle at the top or bottom and cause the stars to look something like tear drops. All too often this is blamed on the optics. Another effect I've seen is that air swirling inside can have a different density at the center and edge, making the correction of a good mirror look wrong.

If you're figuring with the star test, you should, from time to time, test it at the center of curvature with the Foucault test or a Ronchi screen to make sure the surface texture is smooth. Figure smoothness is much more apparent in still indoor air.

When you think you've completed figuring, be sure to test the mirror again on a second night. You may find that exhaustion or the desire to be done with it blinded you to obvious problems, or that the mirror, especially a plate glass mirror, was not allowed to cool long enough the first night. Remember that after a polishing session, a plate mirror needs as long as three hours to equilibrate.

Irregular star images were discussed previously. The key to interpreting these is whether or not the irregularity rotates with the mirror. Also check the diagonal — a bad one can do some strange things to the shape of the star images.

Applying the Dall Null Test

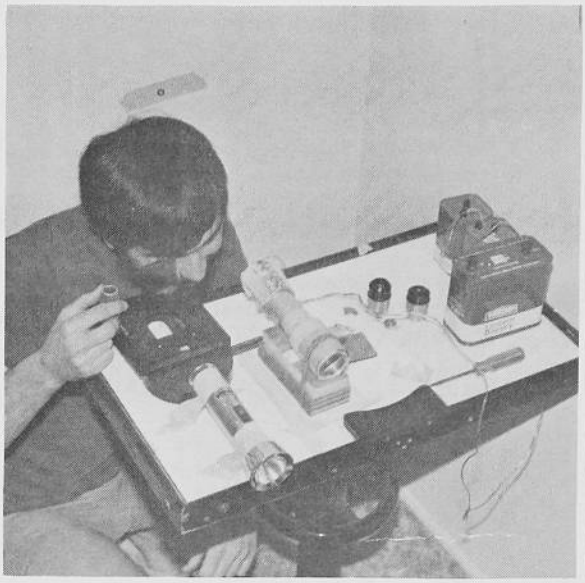
As mentioned before, the Dall Null test is the one I prefer for figuring my own telescope mirrors. Its great advantage is that, like the star test, it is a null test, but without the need of a clear night, a star, a finished telescope, and good seeing. It offers much better control of air turbulence.

Its only real drawback is that you must make and mount a finely figured plano-convex lens. Although lensmaking is manageable enough, it's not a skill many telescope makers have acquired. You must also be able to measure the distance between the pinhole and the lens to .001", a problem solved by access to a good vernier caliper.

Information for performing this test, given a good lens, is found in *Sky & Telescope* for September 1976 on page 210.

I know of no published analysis of this test's sensitivity to small setup errors. It would help TMs if someone were to publish a wavefront analysis of the test setup as a function of error in the focal length of the lens and in the pinhole-to-lens distance, just to see how critical spacing is for different setups and f/ratios.

However, I have done the calculations for a Dall null setup for a 25" f/6 parabolic mirror and a null lens with a 10" focal length. It turns out that the focal length of the lens must be known to better than 1%; an error of 0.005" between pin hole and lens is acceptable, and an error of



±¼" in the placement of the knife edge is acceptable.

For the tester, I find a small slit works better than a pin hole. My tester uses a 12-volt flashlight bulb which isn't really very bright after passing through both a red filter and a pinhole. The slit allows more light than through a pin hole, but must be kept small or the sensitivity of the test will be lost.

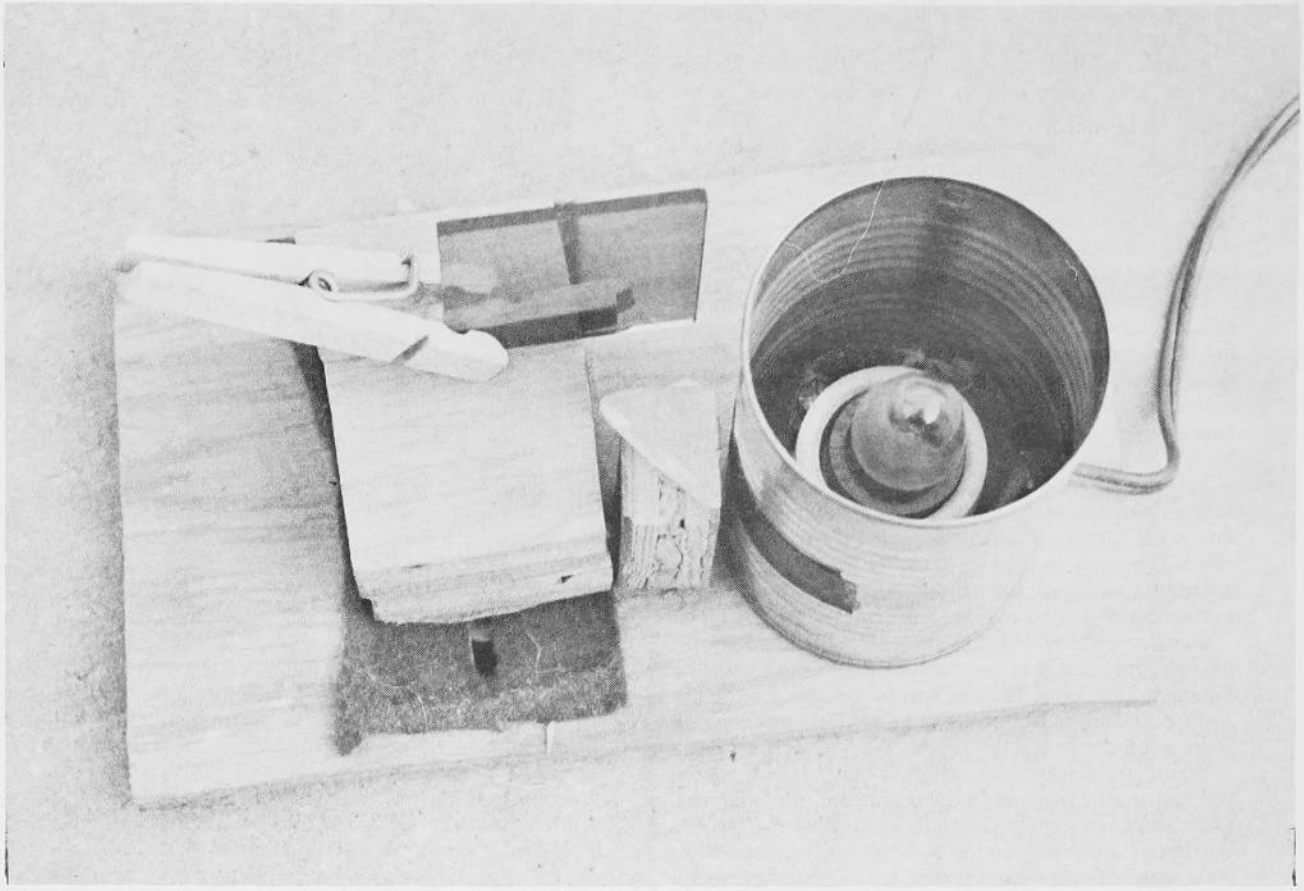
In applying the test, I use both a knife edge and a Ronchi screen to analyze the aberrations in the returning beam. I find the information I get from both very useful.

The problem you will most likely run into with the Dall null test is collimation. Here's how to set it up. Start by placing the mirror so its center of curvature is over your test table. Using a common Ronchi tester, find the exact location of the center of curvature on the test table. It will be necessary to place the knife edge within 0.25" of this location, so place a mark on the table. Now place the Dall null tester already set up for your mirror's correction on the table and aim it at the center of your mirror. Retrieve the return image from your mirror and adjust the tester laterally until the image is just beside it. Find the exact focus with a Ronchi screen and push the test unit forward or backward until the focus lies over the original center of curvature mark you made on the table.

Now comes the hard part: adjust the collimation of the tester until the Ronchi screen lines run regularly across the mirror. If they bend off to one side, rotate the tester left or right to remove it. If the lines bow up or down, tilt the tester up or down to remove it. This step is just like collimating a very fast telescope.

It will speed the next test if you replace the mirror on the test stand in exactly the same place it was the time before so that the center of curvature line on the table does not have to be located each time. However, check it from time to time because figuring the mirror will change its radius.

Once you have the mirror accurately collimated, place a flashlight where it won't get moved (or put it in V-blocks so it can be lifted out and replaced exactly) to shine on the mirror. Then mark on a wall, bookcase or whatever, the exact place the filament comes to a focus off the mirror. Every time you replace the mirror on the test stand, you can line it up on the mark using the image of the flashlight. This should allow the null tester to be very near collimation requiring just minor adjustment. I use this system and can re-collimate the tester in less than one minute once the flashlight image is lined up.



Reading a Ronchi Screen

Many telescope makers who have the necessary testing experience to follow this article may have never found it necessary to learn the Ronchi test. It is a very handy test, relatively simple to interpret, and a good check on the others especially if you're in doubt about what you think they mean.

A Ronchi screen is a piece of glass (preferably), plastic, or film with alternate equally wide opaque and transparent lines on its surface. The number of lines per inch usually lies between 50 and 500. A 150 line per inch screen is suitable for most mirror testing applications.

The Ronchi test is done by placing your eye to receive light from a small source of light and looking through the Ronchi screen. You will see dark "bands" on the mirror surface. The source of light can be a star for null testing in the telescope, or a pinhole, slit, or any light that has first passed through one side of the screen itself for indoor testing.

You will see the mirror surface illuminated as in the Foucault test, but with the addition of the dark bands running across the mirror. As you move the screen toward focus from either side, you'll see fewer and broader lines on the mirror. The farther you move the screen from focus, the more lines you'll see on the mirror.

The more accurately the mirror focuses light, the straighter the lines look. A perfect sphere tested at its center of curvature or a parabola tested at its focus in the telescope on a star both yield perfectly straight lines. However, if you test a parabolic mirror at the center of curvature, or a sphere at focus in a telescope, you will see bent or bowed lines.

The Ronchi test reads slope errors on the mirror which affect the focus of the different parts of the mirror and these, in turn, affect the straightness of the lines in the test.

To interpret the test, you only have to remember that the closer you are to the focus of any given zone, the further apart the lines get and the fewer lines you see. You also must know whether you are inside focus or outside focus. This may seem like an oversimplification to those who are familiar with the test, but it is not. The test can become somewhat difficult to interpret when the problems in the figure are compound and you are forced to make many distinctions as to high and low zones.

Let's try a few examples. If you're testing a sphere at center of curvature with the screen inside focus and the mirror has a hole (shorter radius region) in the center, you'll see straight lines everywhere on the mirror except in the defective center where the lines bow outward, giving fewer and wider lines. Outside focus, you'll see straight lines everywhere but the center where the lines bow into the center.

The reason the center lines bow away from center on the inside of focus is because the sphere has a hole in the center which makes the center zone focus short, and which means the screen is closer to the focus of the center than the rest of the mirror. The consequence of being closer to focus is that the lines are farther apart — exactly what you see when the lines spread apart in the center.

Outside focus, the screen is farther away from the center focus than the focus of the rest of the mirror, causing the lens to push closer together in the center. If the mirror had a hill (long radius region) in the center rather than a hole, the whole thing would be reversed. Inside of focus, the screen would be farther away from the focus of the center and the lines would bunch together in the center.

A mirror with a good figure except for a turned down edge, tested inside focus, shows straight lines across most of the mirror which bow inward at the edge. The defective edge focuses farther away from the screen than most of the mirror. Outside focus, where the edge is closer to the screen than the rest of the mirror, the lines bow away from the center of the mirror.

Interpreting zones midway across the mirror is difficult, but the same rules apply.

Imagine a sphere with a high zone halfway to the edge. A high zone has a short focus on the side toward center and a long focus on the side toward the edge. A screen inside focus shows the inside of the zone is closer than the rest of the mirror, so the bans bow outward from the center. On the outside edge of the zone, the screen will be farther away causing the lines to bow back toward the center. Of course, the opposite appearance is seen on the other side of focus.

One more example is worth mentioning since it can really suprise someone seeing it for the first time. Suppose you have a mirror having zones with different focal lengths, but each zone is spherical. Under test, these parts of the mirror will show straight lines, but the lines will have different spacings. These zones will, of course, be separated by a transition zone that will show up distinctively on the screen.

The sensitivity of the Ronchi test increases as the screen is moved closer to focus. For a null test, the screen is usually placed to show one to five lines. For mirrors with large departures — for example, a paraboloid tested at the center of curvature — the lines will bow so strongly that many lines will be needed.

Testing a parabolic mirror at the center of curvature shows a mirror with grossly bowed lines depicting the correction of the mirror. It is not wise to try to determine whether any mirror has a correct figure this way, for the exact amount of correction is not apparent — only the effects of the correction error can be seen. The Ronchi test is extremely helpful, however, because you can judge whether you have a smooth conic section from how smoothly the lines bow and whether their curve "looks right." Useful figuring information can be gleaned in some circumstances by judging if the curved lines are too curved in one place with respect to the curve in general. This is a skill you'll obtain only by testing many mirrors.

Astigmatism affects the Ronchi lines by causing them to rotate when you go through focus. If the astigmatism is bad, the lines will turn a little clockwise or counterclockwise. With one line on the mirror, astigmatism causes an "S" shape. Severe astigmatism will make many lines look "S"-shaped. The effect becomes less noticeable if the Ronchi bands are lined up with the astigmatism.

You will see many other interesting phenomena when testing with a Ronchi screen due to such things as diffraction. Be aware that they exist, and don't get confused when you discover them while applying the test.

Long and Short, High and Low

When you test a mirror by the usual methods available to amateurs — the Foucault, Ronchi, and star tests — you don't see the high and low zones on the mirror directly, but instead see where they focus with respect to each other. Although the different focal points are caused by the highs and lows on the surface of the mirror, you must always be aware of the relation between highs and lows and the longs and shorts.

When the edge of a mirror has a longer focus than the rest of the mirror, it's called a long edge and is a low zone. But if a high zone runs along just inside the edge of the mirror, the edge side of the high will make the edge long even though the edge may not be low at all. But when the center of a mirror has a longer focus than the rest of the mirror, it's considered high.

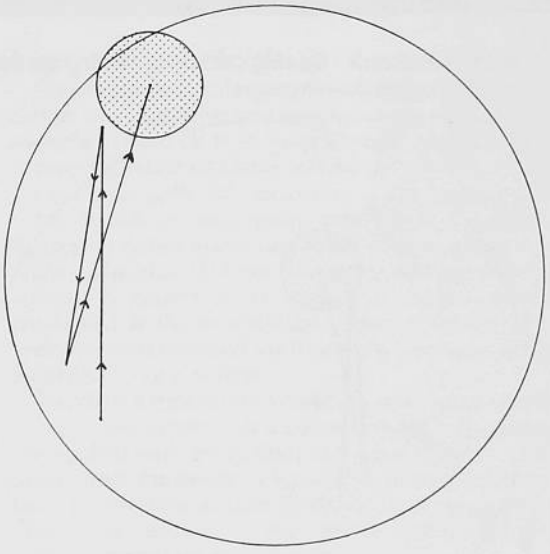
Although most anybody with an interest in mirror making has already come to terms with this, it is impossible to over-emphasize it. When it seems an intractable problem after hours of futile figuring, it is often necessary to re-explain to yourself why a mirror acts like this by drawing light rays reflecting off different curves representing mirror surfaces and see which way they would be reflected by different errors.

Even though the concepts seem elementary, it is very important to keep in mind that when you are testing, you are testing the slopes on the mirror's surface — not the highs and lows that cause the slopes.

Watch out for sneaky highs and lows. A zone that reaches its peak slowly but is a 1/4-wave high may look less severe than a zone 1/8-wave high that slopes up to its peak in a short distance. Ultimately, however, it is the errors from proper focus that end up degrading the final image of a star or planet in your telescope.

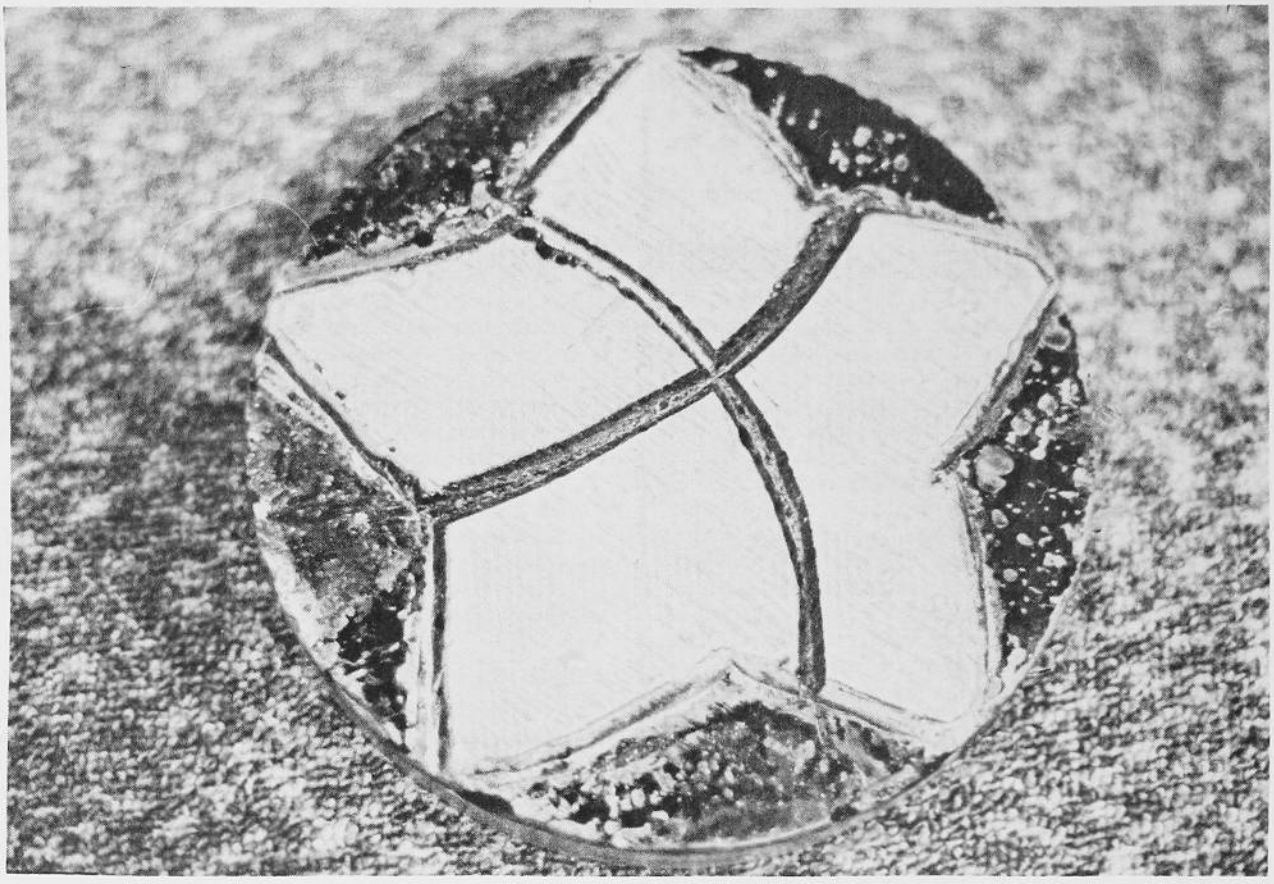
Strokes for Fixing Zones

For working zones with small polishers, the usual polishing action is the tangential stroke and a variation on it called the tangential tree stroke or "V" stroke. The tangential stroke is applied using straight strokes centered on the zone we wish reduced while walking slowly around the mirror.

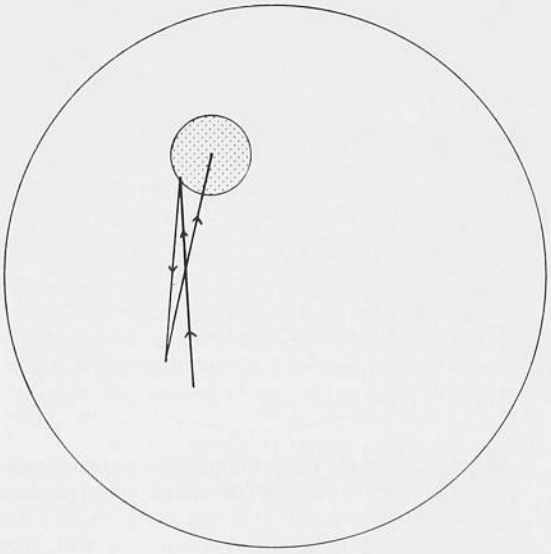


Apply the stroke by pushing the lap forward and then pulling it back in a straight line while taking a step around the mirror and so on. You can progress less than 1" around the mirror per stroke, or you can progress several inches, depending on circumstances and your own personal preference. The length of the tangential stroke will vary with what you wish to accomplish. Short strokes cut more steeply and long strokes tend to cut less steeply and tend to blend into adjacent zones more.

It is very important to maintain the same drag on the lap for each revolution around the mirror, and it is also important to return to where you started without doing the starting point over. Even if you do several revolutions, be sure to stop your last stroke just before the place where the first stroke started. Don't always



start handwork figuring sessions with the same orientation of the mirror.



The tree or "V" stroke branches off to the left or right or both sides of a tangential stroke. This gives you control to widen the cutting action of the lap. Taking strokes with a stroke off toward the center causes the stroke to cut steeper on the edge side and less steeply on the center side. You can branch every stroke, every other stroke, or every third stroke — whatever the problem calls for. Just be sure not to miss sections of the mirror.

Another stroke that serves to widen the effect of a small lap is a "W" stroke done over the zone.

I use these strokes with polishers from 1" to 16" diameter on optics from 16" to 36" diameter on a daily basis in my work. The results even after heavy handwork are amazingly smooth even when tested with sensitive interferometric equipment.

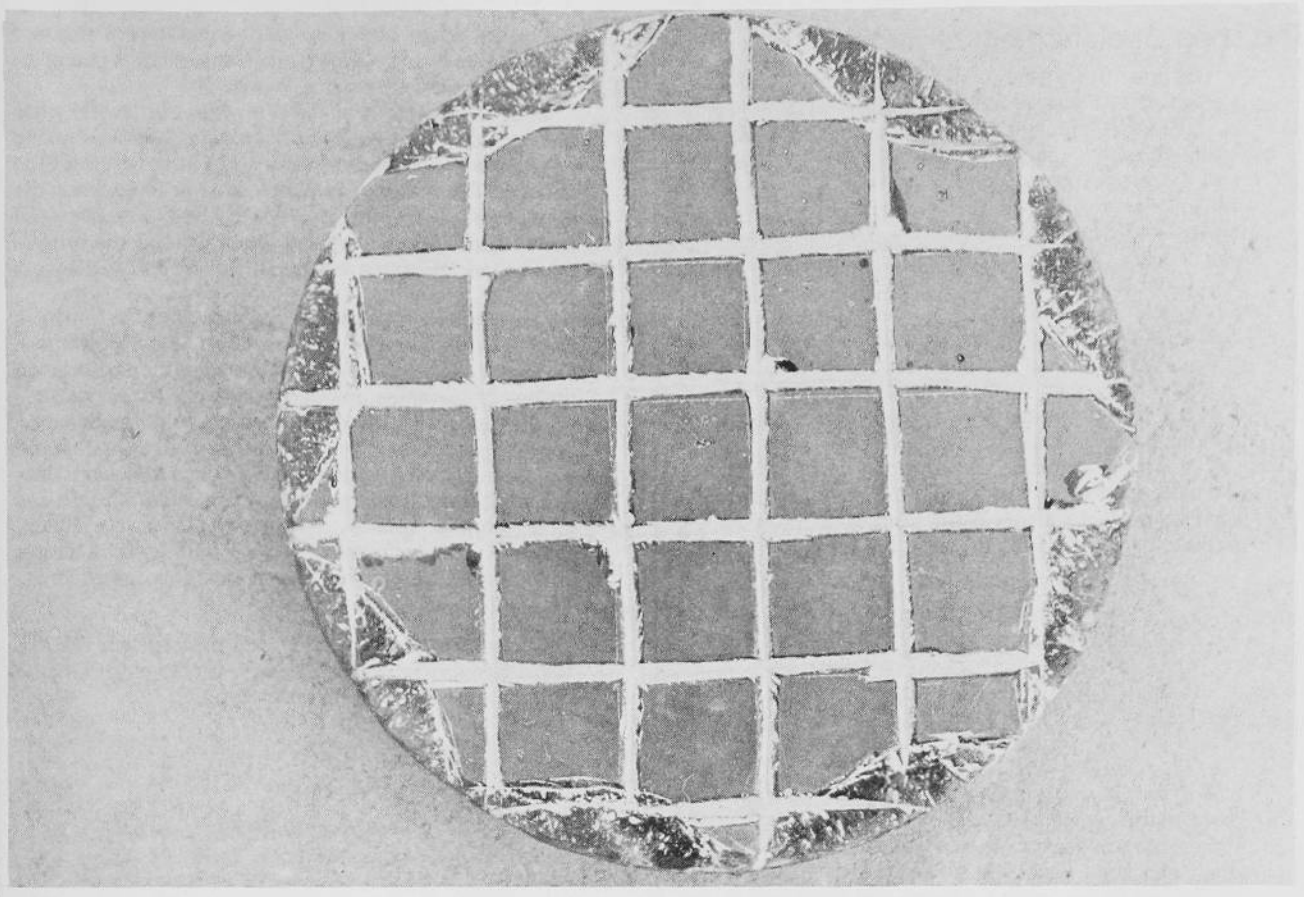
Figuring Laps

Small mirrors are usually parabolized with a full-size lap. The long "W" stroke usually employed works to deepen the center and reduce the edge of an initial sphere until it is paraboloidal. With a 6" f/8 mirror, parabolizing may take under 100 strokes.

A large mirror, however, departs far more from a sphere, enough so that parabolizing with a full-size lap can be a lesson in frustration — to say the least. While an 8" f/6 paraboloid and the best fitting sphere differ by about ½ wave at the 70% zone, a 16" f/5 differs by about 1½ waves. Since a full-size lap has a natural tendency to produce a spherical surface, it works against you. Nevertheless, it is easy to deform an 8" f/6 smoothly by ½ wave. But a 16" f/5 requires very aggressive strokes to deform a sphere smoothly by 1½ waves.

When I first started making big mirrors, I parabolized them with full-size laps. It wasn't until I was having trouble getting enough correction and a smooth curve at the same time on a 16" f/5 that I resorted to using an 8" lap. In no time it was parabolized — and really smooth. The next mirror I did, a 16" f/6, I corrected directly from a sphere with an 8" lap. It was a revelation to me. The mirror went from the sphere to a well-corrected paraboloid with no more than the 8" lap and a general correcting stroke. Since then, I have learned that almost everybody parabolizes big or fast mirrors with smaller laps.

Small laps are used for polishing aspheric correction



and for figuring zones in the mirror, as we will discuss later. Small laps come in many different shapes, but for our purpose, the two main shapes are the star lap and the scalloped lap.

Both forms have their edges "tapered" to allow the correction being done with it to blend in with the rest of the mirror. Small round laps often leave the mirror with a rough surface texture.

For increasing or decreasing the correction of your mirror, a lap less than half the diameter should be used. For a 16″ f/5 or f/6, I would use an 8″ scalloped lap for most of the correcting. For a faster 16″ mirror, I would switch to an 8″ five-point star lap to contour the steeper curve more successfully. For a 24″, a 10″ scalloped or star lap gives good results. As mirrors in this size range get faster, especially under f/5, more deeply cut or smaller star laps become necessary. Your own experience and techniques will determine what you will need.

For figuring zones on the mirror, still smaller laps will be needed. These laps are better off cut to a star shape, except for very small laps that can be scalloped or round for the extreme edge of the mirror. We will talk about this later. It is impossible to tell just how small a lap you will need for zones, since that depends on the zone, but I start by making a 4″ star lap and it does the job on most anything that an 8″ or 10″ lap is too large to handle.

I usually make these small laps on glass mirror blanks or fairly thick aluminum disks. Pitch for these laps should not be too hard or they have a rough feel to them when working. I strongly recommend Adolf Miller #73 black pitch, which was discussed in Part 2.

I groove the large small laps — the 8″ and 10″ sizes — with a standard square pattern and the smaller star laps with just a couple of arcing curves.

Figuring the Paraboloid

Figuring is an endeavor of strategy. The strategy comes into play when you decide how to treat a certain problem. The trick is to keep in mind all the different contours a mirror can have with respect to different foci.

Let's start with the correction of the mirror, which hopefully will be your worst problem at the start of figuring — rather than a bad rolled edge or a hole in the center. The ideal, but not necessary, starting point is a sphere. A sphere is, of course, an undercorrected paraboloid. In the parabolizing stages, whenever we say under or overcorrected, we'll be talking with respect to a paraboloid, not a sphere.

To shape a sphere into a parabola, one can deepen the curve in the center with a correcting lap. If the strokes are applied with perfection, and care is taken not to overcorrect the mirror, it is possible, though unlikely, to bring the mirror to a paraboloid with no other strategies. The same applies if the mirror starts smoothly undercorrected by any amount.

But, most unfortunately, what you are likely to find is that the mirror surface is not a perfect undercorrected parabola, and isn't even a conic section. An inexperienced person isn't likely to correct a mirror without needing several "touch ups" before a parabola is achieved. However, let's start off with the basic correcting strokes, the strokes that increase the correction of the mirror, parabolizing as it is called. We'll do the "touch up" strokes later.

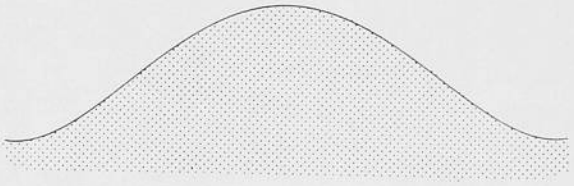
Work with the mirror face up. Start by squirting polishing agent onto its center and smearing it around an area larger than your correcting lap. Place the lap on the mirror for a 5-minute wet press with 10 to 15 pounds on its back. Start every figuring session this way to insure a good fit between the polishing tool and glass.

The Long, Straight, Central Stroke

The first stroke used for increasing the correction is a straight stroke running nearly through the center of the mirror. Push the lap nearly through the center and continue until it's part way over the far edge, then you pull it back nearly through the center until it overhangs the edge near you, then back nearly through the center again — all while you walk slowly around the mirror.

The place where the lap overhangs the edge should be a few inches over from the last stroke. I prefer to move over about one diameter of the pitch lap each stroke, thus making sure not to repeat an area of the mirror on my next time around. It is important, even crucial, when you're working with small laps to be consistent and even-handed. If your strokes vary as you progress around the mirror, irregular errors in the figure will result.

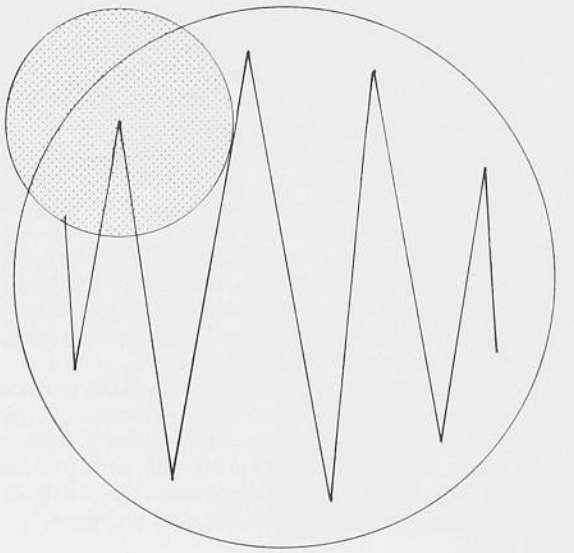
This stroke works on the undercorrected parabola as if it were focused so that all the error was in the center. Usually on fast mirrors it will tend to let the edge lag behind, or, in other words, raise the edge.



The long, central stroke normally doesn't go right through the center, but instead misses it by 1 inch or so. Either side will do, but stick to one side or the other and don't alternate. If you do go directly over the center, you'll tend to overwork that area and get a hole in the middle. On the other hand, too far off center will produce a flat or high center. You have a lot of control in this, so use it. At times, you may want to stroke right through the center to reduce a high middle; at other times, stroke 3 to 4 inches off center to bring up a central low while still adding correction to the mirror. This stroke is very versatile. Once you get a feel for how it works, you can do several things to the figure with it.

The "W" Stroke

The second major correcting stroke is a "W" stroke. It starts at one side of the mirror, hanging over the edge 2 to 3 inches, and proceeds forward and back across the mirror to the other side as you walk around the mirror all the while. Each complete "W" runs 4 to 5 forward strokes, each overhanging the edge slightly per cycle from one side to the other.



The "W" stroke reduces the edges somewhat while also reducing the center. For best effect, avoid stroking heavily over the 70% zone since this serves to reduce the effect you're working for. Don't skip the 70% zone in the literal sense; just work your "W" pattern to cross over it more briefly. Someone watching you do this stroke might not even notice that the 70% zone was getting less work.

I always use both the long central and "W" strokes when correcting a mirror by hand. How fast these strokes change the mirror's correction depends on dozens of variables unique to each telescope maker. I would start with a 15-minute session to get a gauge on how fast it works for you. As the surface departs more and more from a sphere, the strokes will work less effectively on the end as the surface departs more and more from a sphere. Toward the final correction, especially on a fast mirror, you will have to work harder and harder to get a given increase in the correction.

Tangential Strokes

To decrease the correction, you must reduce the 70% zone. Remember that an overcorrected mirror has a high 70% zone relative to a paraboloid.

If you have a full-size lap, polish with a short "W" stroke: this usually brings an overcorrected mirror down very smoothly. If your main polishing lap is subdiameter, using it with a "W" stroke to decrease correction can rapidly flatten the center but leave the edge down, a problem you'd prefer to avoid.

A useful alternative is to use the pitch lap prepared for parabolizing the mirror with a tangential stroke right on the 70% zone. Starting with the lap centered on the 70% zone, push it forward and pull it back along a straight line while you walk slowly around the mirror. This stroke should remain wholly tangential — don't follow the zone with a curved stroke. The tangential stroke reduces the 70% zone and usually tends to bring up the edge at the same time. If the mirror is strongly overcorrected, bringing up the edge will be a problem, and we'll discuss techniques for curing it next.

If, after testing, you see a bump forming in the center, you can add a long center stroke to the tangential stroke. After 3 or 4 tangential strokes, turn and run the lap right through the center of the mirror, then resume the tangential strokes.

Correcting a Low Edge

A low or long edge, whether it is ½" wide or 4" wide, presents the same dilemma — you need to add glass. Since adding glass is impossible, we're forced into either removing glass everywhere else on the mirror or blending the edge into the existing curve and thereby lengthening the overall focus. The second method is much less work.

You can ignore a long edge if it is under-corrected with respect to the final figure. You simply treat it by applying strokes to increase correction without going all the way out to the edge until the center matches the edge.

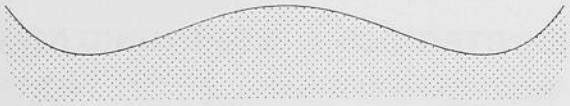
However, when the edge is disproportionately long,

you must deal with it directly so correcting of the mirror can proceed. As an example, we'll take an 18″ mirror about 50% parabolized with an edge zone 2″ wide rolled-off with respect to a curve focused midway.

One way to fix it is to use a small lap, say a 3″ or 4″ star lap, to work the region just inside the edge. The stroke is a tangential stroke centered on the peak. Start with a well-pressed small star lap. Push the lap straight back and forth tangent to the center of the mirror while progressing 1″ to 2″ around the mirror between each stroke.

The result is that the figure will change to the dotted curve:

This can be refocused to:



The figure now warrants a general correcting stroke that will also blend in any "zoniness" caused by the small lap on the edge.

The single tangential stroke won't do the whole job unless the edge is just slightly rolled. To increase the blending action toward center, a "V" stroke is used in conjunction with the tangential stroke. You start with a normal tangential stroke forward and back, then you add a stroke that veers off toward the center 1″, 2″, or more inches, depending on what is needed. How often side strokes are added, whether every stroke or every third stroke, can only be determined by examining the problem on the mirror. The "V" stroke will cause the zone you are doing to slope less on the side that gets the "V" — just what's needed for the mirror in this example.

How much work will it take? This is determined by testing and evaluating the progress. Times typically range from one trip around for a very slight zone to 30 minutes of hard work followed by smoothing with a large polishing lap for gross zones.

With a rolled edge, a problem you may encounter is getting the last 1″ or so of the edge to come into line. For this, a 2″ scalloped lap may be needed, especially if the very edge is lagging behind. Apply the scalloped lap with a circular stroke, allowing the lap to overhang the edge ¼″ to ½″, while progressing around the mirror. Always keep the lap the same amount over the edge — and be aware that although this work contours the slope of the edge up, it will leave a long zone a couple of inches wide inside the edge that you'll have to deal with later. Use the circular stroke technique sparingly, and use it early in figuring, since it may take considerable smoothing with your largest lap to repair the damage of fixing the edge.

If you have a turned edge that is not perched on an undercorrected curve, the same techniques apply except you will use them at the expense of the center of the mirror. Work the edge as described, but blend the curve much farther into the center. The resulting high center then can be worked with a subdiameter lap.

After extensive work with a small figuring lap, a smoothing session with your polishing lap or a correcting lap may be necessary.

The Turned-Down Edge

The much dreaded "TDE," or turned-down edge of *ATM* Book 1 fame, is a long or rolled edge only ¼″ to ½″ wide. You must deal with it as soon as you detect it, since the figure of the whole mirror may suffer in repairing it.

A full-size lap can sometimes eliminate the TDE if you use short strokes back and forth with no side motion. A lap the size of a silver dollar can also be used in much the same way a 3″ or 4″ star lap is used for the similar problem of a broader low edge. Hang the round lap over the edge around ¼″ and proceed with circular strokes around the mirror. Remember, for a circular stroke, the lap must always hang off the edge ¼″. This will usually turn the edge up in a short time because even though turned edges slope sharply, they are often not very far down. This technique leaves a low zone inside the edge that you must smooth with a larger lap — luckily, a problem many times more manageable than the rolled edge itself.

High Zones

High zones can be handled directly with the tangential stroke. The trick is to determine the exact shape of the zone and apply a stroke designed to remove it. If you get a high zone that rises very steeply on the center side but drops slowly toward the edge, remove it with a tangential stroke on the crest of the zone with an added "V" stroke toward the edge on every other stroke. This will work on the crest while putting less action down the slope toward the edge where it needs a wider action.

In a case where the high zone is wider than your star lap, within reason, you can widen the action of your star lap by using "V" strokes centered on the zone but branching off to both left and right. Be careful not to do too much work — you want to avoid cutting a low in the center of a high zone by not spreading the action of your small lap.

Central bumps are best treated with a "W" stroke on them while you circle the mirror. Of course the size of the lap and the length of the stroke depend on the width of the bump. Again, remember to spread the work. A common mistake is cutting a small hole in the center of a central bump. Be careful not to underestimate the diameter of the bump.

Low Zones

Low zones are treated by reducing the mirror in a general fashion on either side of the low zone, then smoothing. This is very effective. For a small hole in the center, work down the sides of the hole until you've blended it into the rest of the mirror. By smoothing with a large lap, or "refacing the curve," a small hole in the center can vanish almost like you have the ability to add glass.

A Final Word

If you use indoor tests all through figuring, put the unaluminized mirror into the telescope from time to time and triple-check its progress.

With large mirrors, figuring sometimes goes smoothly and sometimes doesn't. Don't give up. But if things seem to get worse every time you work, make sure you're interpreting the test results correctly. If in doubt, use several tests before doing more work. Think strategically — that's as important as the polishing.

Bob Kestner
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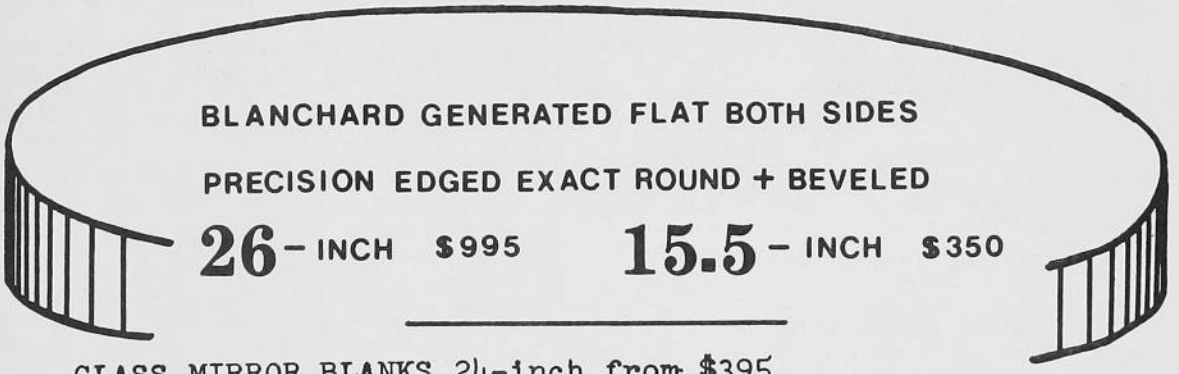

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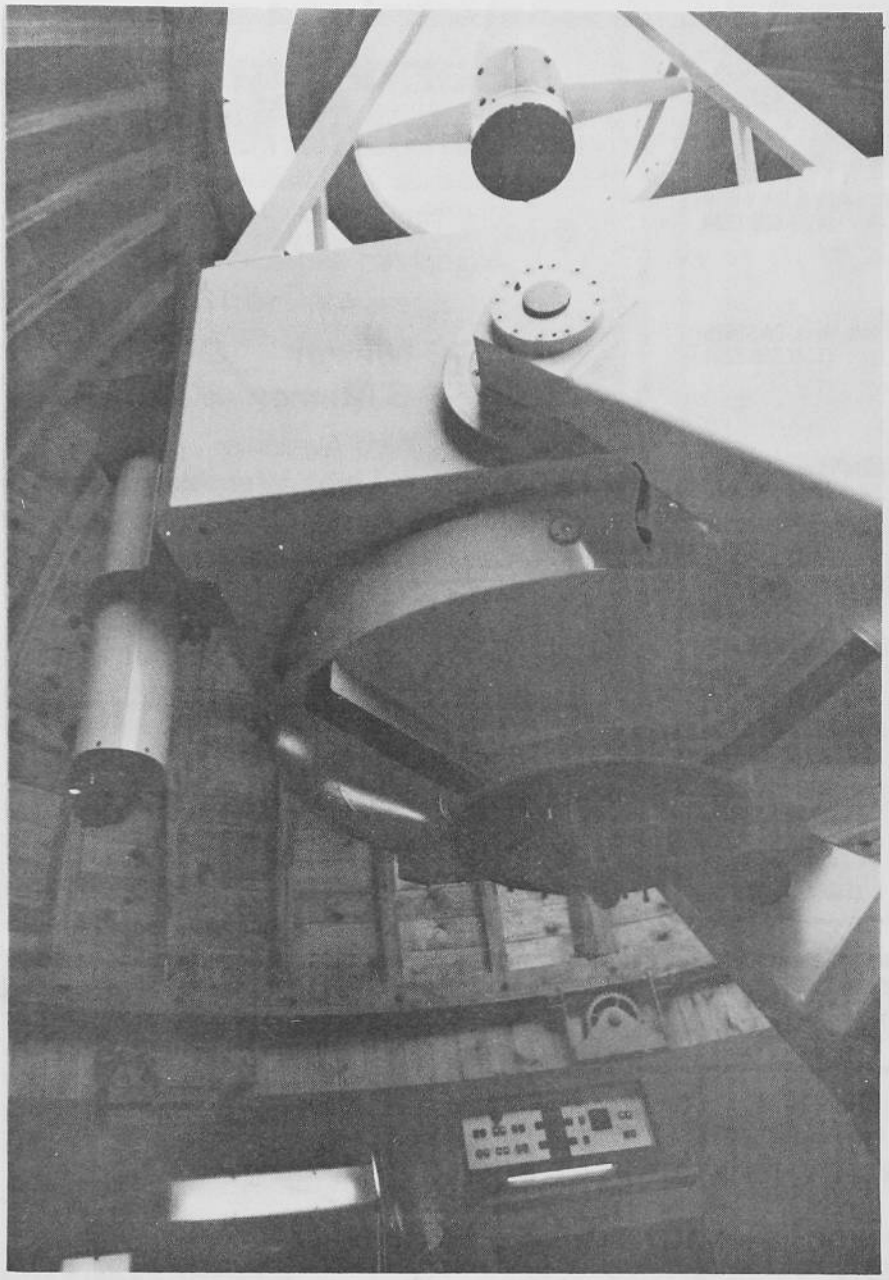

◄4 Letters

eyepiece rack on the side. The front piece is U-shaped with wheels. I also have a six-sided tube that fits into the slot and makes it easier for me to put the tube into the mounting by myself. The tube itself is a typical breach-loading type that allows me to remove the mirror when I'm not observing.

Steven Hubbard
52A Flanders Rd.
Westboro, MA 01581

One-Meter Amateur Reflector

Dear Richard / In my correspondence with amateur and professional astronomers around the world on the subject of photoelectric photometry, the closely related subject of telescopes and telescope making often crops up. Dr. A. Purgathofer at the Institut für Astronomie in Vienna brought to my attention the 40-inch reflector made entirely by amateur astronomer R. Pressberger, and installed on the top of his house near Vienna.

The primary f-ratio is 2.6 and the total effective f-ratio is 9.0. The beautiful wooden dome of 15-feet diameter clears the telescope by less than 1 inch. Herr Pressberger ground his mirror at the Institut für Astronomie using a grinding machine made from a meat cutter, car gears, a food elevator, and a washing machine. Photos of the telescope and grinding machine are enclosed. Just thinking about all the photons I could count from faint eclipsing binaries with such a telescope gives me a serious case of aperture fever!

Russell M. Genet
Fairborn Observatory
1247 Folk Road
Fairborn, OH 45324

— Watch it, Russ! Aperture fever is deadly.

Consumer Reporting

Mr. Berry / I would like to add my voice to those asking for frank, analytical reports of commercially available astronomy equipment.

Look at any journal from the robust hobbies of photography or motorcycling — they tear down and evaluate all sorts of commercial products. This is good for the industry, not bad, and is good for the consumer as well.

I feel this sort of expert reporting is badly needed in astronomy, and urge you to assume a more active role in this area.

Dennis Donnelly
532 N. Hayes
Pocatello, ID 83201

Crunch!

Gentlemen / There is a potential problem with the nested-corner equatorial platform that anyone contemplating building one must be aware of. Be sure to leave clearance between the side of the box and the telescope tube. When looking east, the bottom of the tube swings out to the west considerably outside the circle I designed into my platform. If the platform is built for telescopes with the hinge face on the east side, then the interference is, of course, encountered when pointing the scope west.

Chuck Olson
20832 Greenleaf Dr.
Cupertino, CA 95014

— Thanks for the warning. Next issue we'll be running another article by an Ottawa amateur who independently invented the nested corner design with a very clever drive. His doesn't hit — just be sure to leave enough space.

Electronics Anyone?

Dear Mr. Berry / Would you be interested in a series of articles on basic electronics for TMs in TM? I'm thinking about basic info slanted to the needs of the non-electronic person who'd like to get into it. Examples might be "Troubleshooting" or "Printed Circuits for TMs."

Fred L. Redburn
5518 16th Place
Lubbock, TX 79416

— Thanks very much for offering, but I think that we'd begin to stretch the basic definition of the magazine too far if we published very many such articles, valuable as they might be. If I am wrong, readers, please correct me.
— RLB

Leak Fixed — and Thanks

Dear Mr. Cox / In TM#12 you printed my letter requesting help for a leaking observatory.

I just wanted to thank you and all the many amateurs who responded. Numerous suggestions for help came from many quarters — some very excellent ones, I might add.

I appreciate very much the effort that each one made to assist a fellow astronomer.

Pastor Richard Steeg
Rt. 3, Box 268-B
Gaston, OR 97119